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by J. FINDLATER, T. N. S. HARROWER, M.A., B.Sc.,
G. A. HOWKINS, M.B.E., B.Sc. and H. L. WRIGHT, M.A.

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SUMMARY

Winds at the surface and 900 mb for the two ocean weather stations India and Juliett were compared objectively. Similar comparisons were made of the surface winds at Leuchars and London (Heathrow) Airport with 900 mb winds at the nearby radiosonde stations Shanwell and Crawley respectively. A basis was obtained for forecasting the surface wind from the geostrophic wind for sea areas but not for land areas. However, the data are of interest in relation to general questions of turbulence and are presented in some detail. The paper is in four main sections:

1. Introduction, including a description of the data used and the method of analysis.
2. Discussion of results and comparisons with some other published data. (Summary at para. 2.9.)
3. A possible forecasting technique.
4. Appendices dealing with some special features affecting the validity of the results.

1. INTRODUCTION, DESCRIPTION OF DATA AND METHOD OF ANALYSIS

1.1. *Introduction*

This paper summarizes work on this subject by the Forecasting Techniques Branch of the Meteorological Office, Bracknell, from 1960 to 1964. For much of this time the work was carried out by J. Findlater under the direction of H. L. Wright and unpublished papers by these authors have been drawn upon freely. The basic data were assembled during a search for an objective technique for forecasting the surface wind at anemometer height (usually 10 metres) from the geostrophic wind derived from a forecast chart of surface isobars. Geostrophic winds are not readily available and measured 900 mb winds were used in the investigation instead. The justification for using 900 mb winds and the difficulties created are discussed in Appendix A.

1.2. *Data used*

Data for the two ocean weather stations India and Juliett were selected to represent conditions at sea. Two land sites were also chosen. Surface winds at London (Heathrow) Airport were compared with 900 mb winds at Crawley and surface winds at Leuchars were compared with 900 mb winds at Shanwell. The effect on the analysis of using surface and 900 mb winds from different locations is small (see Appendix B). Upper air soundings are made every 12 hours, balloons being released at 0200 and 1400 GMT up to 31 March 1957 and at 2300 and 1100 GMT from 2300 GMT on 31 March 1957. The winds at 900 mb were compared with surface winds for the

same time. Ascents commencing at 0200 GMT were grouped with those at 2300 GMT and ascents at 1400 GMT were grouped with those at 1100 GMT. The following data were used:

Station	Height of anemometer† *metres*	Period	Number of observations
OWS I (59°N, 19°W)	17 to 20	1951–60	5556
OWS J (52°30′N, 20°W)	17 to 20	1951–58	4728
London (Heathrow) Airport and Crawley	10	1954–61	4090
Leuchars and Shanwell	12	1957–61	2532

† Height above sea level or ground level.

The following cases were excluded:

(i) incomplete observations,

(ii) all occasions of calm surface wind and

(iii) all occasions of 900 mb wind < 10 kt.

There were few cases of surface calms associated with 900 mb winds exceeding 9 kt at the ocean weather stations but 20 per cent of Leuchars night-time observations, with 900 mb winds between 10 and 19 kt, were associated with calms at the surface. However, the mean surface wind for this range of 900 mb wind speed was only 5 kt and therefore the effect of excluding surface calms was small.

1.3. *Data treatment*

Numerous investigations (Frost,[1]* Marshall,[2] Wilson[3,4,5]) of the wind profiles near the earth's surface have shown that the wind at anemometer height depends on the following factors:

(i) character of the underlying surface ('roughness'),

(ii) height of anemometer and proximity to buildings or other obstructions,

(iii) orography,

(iv) temperature lapse rate in the lowest layers,

(v) wind strength, and

(vi) time of day and possibly of year.

With the above factors in mind observations were sorted into the following five main groups:

(i) day-time (1100 and 1400 GMT), night-time (2300 and 0200 GMT). This division was made at land stations only and all four observations were combined at the ocean weather stations,

(ii) four seasons; winter (Dec.–Feb.), spring (March–May), summer (June–Aug.), autumn (Sept.–Nov.),

(iii) six classes of temperature lapse rate (defined below),

(iv) five classes of 900 mb wind speed, in the ranges 10–19, 20–29, 30–39, 40–49, $\geqslant 50$ kt, and

(v) eight classes of 900 mb wind direction, in 45° sectors centred at true N, NE, E, etc.

The temperature lapse rate was defined as the temperature difference between the surface and the 900 mb level, divided by the height of the 900 mb surface above the station. The surface temperatures used in the two land station analyses were those at Heathrow and Leuchars—not those

* The superscript figures refer to the bibliography on page 15.

at the radiosonde stations Crawley and Shanwell. Observations were recorded in degrees Fahrenheit and feet up to 31 March 1957 and the temperature lapse-rate classes (henceforth called 'lapse classes') were defined in these units as follows:

Lapse class	1	2	3	4	5	6
Range of temperature lapse rate degF/1000 feet	$\geqslant 5{\cdot}5$	4·0 to 5·4	2·5 to 3·9	1·0 to 2·4	−0·5 to 0·9	$\leqslant -0{\cdot}6$

Data which have become available recently from instruments exposed on high masts (Jehn and Durie,[6] Thuillier and Lappe[7]) have raised doubts about the relevancy of the lapse class as defined above (see Appendix C).

1.4. *The computer programme*

Temperature lapse rates were calculated automatically from data tapes of 900 mb and surface temperatures and 900 mb heights. Each observation of surface wind was resolved into two components—a *p*-component along the 900 mb wind direction (positive in the 900 mb wind direction) and a *q*-component at right angles to the 900 mb wind direction (positive towards low pressure). Each component was expressed as a fraction of the 900 mb wind speed. Components were sorted into classes in the various ways listed at para. 1.3. and means and standard deviations were printed out for several combinations of classes. All combinations were based on the following standard table, which was printed for each of the six lapse classes:

900 mb wind direction class	900 mb wind speed class (knots) 10–19	20–29	30–39	40–49	⩾ 50	All speeds
N						
NW						
W						
SW						
S						
SE						
E						
NE						
All directions						

Data for all four stations were also sorted into the four seasons and, for the two land stations but not for the two ship stations, into day-time and night-time observations. Altogether there were 960 classes for each ocean weather station and 1920 classes for each land station.

1.5. *Arrangement of data*

There are insufficient observations to produce reliable means for all the above-mentioned classes and some combination was essential. Data for all four seasons were combined and, for the two ocean weather stations, classified either into six lapse classes and five 900 mb wind speed classes discarding the direction classes (Tables XIII (*a*) and (*b*)), (see p. 21) or into six lapse classes and eight 900 mb wind direction classes discarding the speed classes (Tables XIV (*a*) and (*b*)), (see p. 24). Similar classifications were adopted for the two land stations but the division into day-time and night-time observations was retained in the classification by lapse class and 900 mb wind speed

(Tables XIII (*c*)–(*f*)) in view of the doubt already expressed about the lapse classification (Appendix C). Combination of classes may obscure the full effects of the classifying parameter if it is correlated with others temporarily discarded (Appendix D).

1.6. *Method of presenting results*

1.6.1. Means and standard deviations are given in Tables XIII and XIV. Means are also plotted in Figures 1 to 13* where the effects of the various classifying parameters on the means are more readily compared. Where there is space in the diagrams, the numbers of observations used in calculating the means are shown in brackets beside each plotted point but frequent reference should be made to the tables for standard deviations, which are large in all classes. Whenever practicable the mean values of p and q are plotted in graphical form using rectangular axes. A unit vector along the p-axis represents the 900 mb wind and a line drawn through the origin to a point in the diagram with co-ordinates p, q represents the surface wind, the speed being expressed as a fraction of the 900 mb wind speed. Therefore the diagram has the merit of representing in a single figure the mean values of p, q, surface wind and the angle (α) between the surface and the 900 mb wind directions. However this diagram proves confusing when two classifying parameters are used simultaneously and yield 30 or more values for plotting in a single diagram. In such cases it is more convenient to plot independently either the p and q ratios or the surface wind speed (expressed as a fraction of the 900 mb wind) and the angle α between the two winds.

1.6.2. The following symbols are used for convenience:

V_0 =wind at anemometer height

V_{900}=radar wind ascribed to the 900 mb level

V_G =geostrophic wind, for mean sea level

α =angle between V_0 and V_{900} (positive when V_0 is backed with respect to V_{900})

p =component of V_0 along V_{900}, expressed as a fraction of V_{900} and reckoned positive in the direction of V_{900}.

q =component of V_0 at right angles to V_{900}, expressed as a fraction of V_{900} and reckoned positive in the direction of low pressure.

p and q are sometimes referred to in the text as component ratios or simply as ratios.

2. DISCUSSION OF RESULTS

2.1. *Overall means* (*Figure* 1)

2.1.1. The mean value of α at sea (8°) agrees with the mean value quoted by Westwater[8] and the mean value of 20° for the two land stations agrees with Frost's[1] computed figure for zero temperature lapse rate. Bradbury[9] suggests a higher mean of about 30° based on data for Gorleston analysed by Durst.[13] The mean value of V_0/V_{900} at sea is 0·8 which is somewhat higher than the mean of 0·7 found by Gordon[14] and the mean of about 0·6 suggested by Frost.[1] The mean value of 0·4 for Heathrow and Leuchars is in general agreement with various data for land stations quoted by Bradbury.[9]

2.1.2. There are small differences in the V_0/V_{900} ratios for the two ocean weather stations which persist even when data are classified by lapse rate, 900 mb wind speed and 900 mb wind direction (Figures 2–4). The values of V_0/V_{900} bear nearly the same ratio to each other as do the sines of the latitudes of the two positions. Frost[1] obtained an expression (equation 48 in his paper) which, for a given pressure gradient, requires the ratio V_0/V_G to be proportional to $(\sin^2 \phi)^{m/(1+2m)}$, where ϕ

* All figures, and relevant notes, appear on pp. 29–41.

is the latitude and m is a stability parameter. The modal value of m at sea is about 1/5 (corresponding to a temperature lapse rate of approximately 4 degF per 1000 feet), which makes V_0/V_G proportional to $(\sin \phi)^{2/7}$, and Frost's formula does not wholly explain the observed variation of V_0/V_{900} with latitude. The mean 900 mb height at OWS I is about 50 metres lower than at OWS J and, if the distributions of the heights about these mean values are similar at the two stations, then there should be more occasions at OWS I when the 900 mb height is sufficiently low for surface friction effects to become incorporated in the reported 900 mb wind (Appendix A). Such friction effects would reduce the mean value of V_{900} and increase the V_0/V_{900} ratio. The mean 900 mb height is lower at Leuchars than at Heathrow but the V_0/V_{900} ratio is less at Leuchars—probably because the surrounding terrain is generally rougher at Leuchars.

2.2. *Effects of lapse rate*

2.2.1. The highest V_0/V_{900} ratios (Figures 2(*a*) and (*b*)) occur at all four stations in the most unstable conditions and are accompanied by the smallest angles α. The ratios decrease and the angles increase through lapse classes 2, 3 and 4 but in lapse class 5 (isothermal) at the two ocean weather stations a sharp decrease in the V_0/V_{900} ratio is accompanied by a small decrease in the angle α. The trend between lapse classes 5 and 6 differs at all four stations. There is a sharp increase in the ratio at OWS I which may be caused partly by a thermal wind component associated in this lapse class with an unusually high proportion of 900 mb winds with easterly components (para. 2.4.1). No such trend occurs at OWS J and at Leuchars there is a sharp decrease in V_0/V_{900} ratio in lapse class 6. Frost[1] predicts a minimum value of V_0/V_G ratio in isothermal conditions (lapse class 5) but a subsequent increase during marked inversions. There is evidence of the minimum in lapse class 5 but no conclusive evidence of an increase in lapse class 6. Variation of surface roughness with wind speed is discussed at para. 2.3.1. and provides a plausible explanation of the apparently anomalous behaviour of the V_0/V_{900} ratio in lapse class 5 as follows.

2.2.2. The assumptions are made that the frictional drag of the sea surface depends on the degree of surface roughness and that air parcels retarded by surface friction are spread by turbulence through a deep layer in thermally unstable conditions. As the temperature lapse rate decreases, the effects of surface friction will be confined to shallower layers and the magnitude of the frictional effect at the anemometer will increase, causing the wind at anemometer height to decrease and back. However, as the wind near the sea surface decreases, smaller sea waves will be produced and surface roughness (see para. 2.3.1.) should decrease. Consequently the air near the surface can accelerate, so opposing the trend of the anemometer wind to back and decrease as the air becomes more stable. The trends are more readily seen in terms of the q-ratio (see para. 2.2.3.) than in V_0/V_{900} ratio and α. The q-ratio is zero by definition at 900 mb and, if the 900 mb wind represents the wind undisturbed by surface friction, the magnitude of the q-ratio of the wind at anemometer height provides a convenient measure of the turbulent surface frictional effects.

2.2.3. Figures 5(*a*) and (*b*) for the two ocean weather stations show that the variation of the p- and q-ratios by lapse and speed classes show a considerable degree of consistency. The p-ratios decrease with increasing stability up to and including lapse class 5. The q-ratios increase up to lapse class 4 but decrease in lapse class 5 in all but the strongest wind speed class and the changes by lapse class are consistent with the sequence of events expected at the anemometer as increasing stability concentrates the surface frictional effects in the lower layers but the sea surface becomes smoother as the surface wind decreases. The p- and q-ratios in lapse class 6 behave in a very irregular manner to which no significance can be attached in view of the small number of observations and large variances. There is very little pattern to the changes in p- and q-ratios for the two land stations (Figures 5(*c*)–(*f*)). The effect of lapse class appears to be restricted in the stronger

900 mb wind speeds, when increased turbulence in the stronger winds tends to establish a neutral temperature lapse rate (class 3) in the lower layers. Lapse class has less effect at night than during the day-time, especially at Heathrow (Appendix C).

2.2.4. It is evident from Figures 1, 2(*a*), 3(*a*) and 3(*b*) that, although small changes of the angle α accompany changes in the 900 mb wind speed, α at sea is determined primarily by the lapse class. Frost[1] derived the expression

$$\alpha = \frac{m}{m+1} \cdot \frac{\pi}{2}$$

which makes α depend solely on lapse rate. Although the derived values of α are in good agreement with observations for lapse classes 4 and 5, the values for less stable classes are too large (Table I).

TABLE I. *Effect of lapse class on α, at sea*

Lapse Class	1	2	3	4	5
DegF/1000 ft	$\geqslant 5{\cdot}5$	4·7	3·2	1·7	0·2
m (after Frost)	$<0{\cdot}17$	0·18	0·22	0·26	0·29
Calculated $\alpha°$ (after Frost)	<13	14	16	19	20
Observed mean $\alpha°$ (OWS I and J combined)	<1	4	12	19	18

The formula also implies a maximum α of 45° but this value is exceeded at both Heathrow and Leuchars. The analysis for Heathrow of α in 900 mb wind direction classes and lapse classes (Figure 12) shows the general dependence of α on lapse rate, as required by Frost's expression, but there is also a wide variation in the range of α by lapse class in different 900 mb direction classes. In the north-east and west 900 mb direction classes the range is about 60°. Greater ranges, exceeding $+100°$ to $-20°$, occur at Leuchars where the pattern of change imposed by the lapse class appears to be completely obscured by the effects of the orography in some directions.

2.3. *Effect of wind speed*

2.3.1. *At sea.*—At sea there is a steady decrease in the V_0/V_{900} ratio as wind speed increases (Figures 3(*a*) and (*b*)). Frost[1] derived an expression which in constant temperature lapse rate conditions would require that

$$\frac{V_0}{V_G} \propto \left(\frac{1}{z_0^{2m} V_G}\right)^{\frac{m}{1+2m}}$$

where z_0=surface roughness length and m is a stability parameter. The median value of the temperature lapse rate at sea is about 4 degF per 1000 ft, which corresponds to a value of $m=1/5$ in Frost's paper. Therefore

$$\frac{V_0}{V_G} \propto \left(\frac{1}{z_0^{2/5} V_G}\right)^{1/7}.$$

The dynamic roughness at sea probably varies with the wind speed and Charnock[10] has suggested that it is proportional to U_*^2 where U_* is the so-called friction velocity. In Table II below, the relative ratios of the observed values of V_0/V_{900} for each of the five 900 mb wind speed classes (taking V_0/V_{900} for 900 mb speed class 20–29 as unity) are compared with the values obtained from Frost's formula when z_0=constant, $z_0 \propto V_G^2$, and $z_0 \propto V_G$.

TABLE II. *Comparison of V_0/V_{900} ratios observed at sea in different 900 mb wind speed classes with calculated values after Frost and Charnock.*

900 mb wind speed class (kt)	10–19	20–29	30–39	40–49	⩾50
Observed mean V_0/V_{900} ratios OWS I and J Tables XIII (*a*) and (*b*)	0·88	0·81	0·75	0·71	0·67
Observed V_0/V_{900} ratios with respect to class 20–29 kt as unity	1·09	1	0·93	0·88	0·84
Calculated V_0/V_G (after Frost[1]), z_0=constant	1·08	1	0·96	0·92	0·89
Calculated V_0/V_G (after Frost[1] and Charnock[10]), $z_0 \propto V_G^2$	1·14	1	0·92	0·86	0·82
Calculated V_0/V_G (after Frost[1]), $z_0 \propto V_G$	1·11	1	0·93	0·89	0·85

The observations fit best with the assumption that $z_0 \propto V_G$, in which case Frost's power law reduces to $V_0/V_G \propto 1/V_G^m$ or $V_0 \propto V_G^{(1-m)}$. In exceptionally strong winds it is observed that sea waves tend to be disrupted and in these conditions z_0 may be reduced. The *p*- and *q*-ratios for several cases of exceptionally strong winds are listed in the inset tables between Figure 5(*a*) and Figure 5(*b*). Although the *p*-ratios still decrease with increasing wind speed, in all but one case the values exceed the average for the appropriate lapse class as plotted in the figures and it seems possible that the decrease in *p*-ratio with increasing wind speed is not continuous throughout the entire range of wind speeds.

2.3.2. *Over land.*—At Heathrow the initial tendency at low wind speeds for the V_0/V_{900} ratio to decrease as the 900 mb wind speed increases is reversed at higher speeds. From Frost's equation 48, when the surface roughness length z_0 is constant, $V_0/V_G \propto (1/V_G)^{m/(1+2m)}$ and the V_0/V_{900} ratio should decrease as the V_{900} wind speed increases so long as V_{900} approximates to the geostrophic wind. Boyden's data for Crawley (Appendix A) indicate that this is true for geostrophic wind speeds up to 25 kt but, at higher speeds, surface friction effects appear to reduce the 900-metre wind as follows:

900-metre wind speed	35	45	55 kt
Geostrophic wind speed	38	50	63 kt

At Crawley the modal value of the lapse rate lies in class 3 for 900 mb winds exceeding 30 kt, which corresponds with a value of m=0·22. With this value of m Boyden's figures for $V_{900\text{metres}}$ and V_G fit Frost's expression closely and, at high wind speeds, the power law may apply to heights above 900 metres. The changes in V_0/V_{900} ratio with 900 mb wind speed at Leuchars, although small, show a trend opposite to that at Heathrow and the ratio increases as the 900 mb wind speed increases. Geostrophic winds are not yet available for Leuchars or Shanwell.

2.4. *Effect of wind direction*

2.4.1. *At sea.*—At sea the V_0/V_{900} ratios and their associated angles α vary with 900 mb wind direction in a broadly similar manner at ocean weather stations I and J (Figures 4(*a*) and (*b*)),

although the magnitudes differ (para. 2.1.). The variation is such as to cause the end of the surface wind vector to execute a roughly elliptical rotation in the diagrams. This rotation could be caused by an approximately constant thermal wind in the surface–900 mb layer. Sheppard *et alii*[12] pointed to the importance of the thermal wind and Findlater, in an unpublished paper, demonstrated that the mean thermal wind is about 255° 2 kt near OWS I and J, whatever the direction of the 900 mb wind (Appendix A). A constant thermal wind would produce circular loops in Figures 4(*a*) and (*b*) with the points representing southerly winds at the top of the diagram and the points representing northerly winds at the bottom. Correlation (Appendix D) of unstable lapse classes (large p, smaller q) with 900 mb northerly winds and stable lapse classes (smaller p, large q) with 900 mb southerly winds probably accounts for the distortion of the loop into an ellipse with the points representing northerly and southerly winds at the ends of the major axis, the axis being orientated in a manner to be expected from Figures 2(*a*) and (*b*). Also, if the thermal wind is constant in speed and direction, the size of the area swept out in Figure 4 should decrease as the mean 900 mb wind speed increases. This is demonstrated in Figure 8(*a*) for OWS I by splitting the data into two parts, one containing 900 mb wind speeds between 10 and 19 kt and the other containing all higher 900 mb wind speeds. The corresponding Figure 8(*b*) for OWS J, although less conclusive, shows the same trend. A mean westerly thermal wind associated with an abnormally high proportion of easterly 900 mb winds partly accounts for the high V_0/V_{900} ratio in lapse class 6 at OWS I (para. 2.2.1.). About one-third of the 35 observations in this lapse class occurred with winds having easterly components when the mean westerly thermal wind opposes the 900 mb flow and increases the V_0/V_{900} ratio.

2.4.2. *Heathrow.*—At Heathrow the distribution in 900 mb wind direction classes (Figure 4(*c*)) bears some resemblance to that at the ocean weather stations and thermal wind effects may still predominate. The effects of orography and surface roughness are also however very important but it proved impossible to separate these from possible thermal wind effects. The lapse rate at night tends to be predominantly stable (Figure 5(*d*)) and an analysis of night-time observations was attempted for the four seasons separately in the hope that this might reveal persistent features of the pattern which could be ascribed to orography and surface roughness. The patterns were very variable, the only persistent feature being a tendency for high values of the cross-wind q-ratio in south-easterly 900 mb winds and it is possible that a significant, variable thermal wind component exists in the surface–900 mb layer. The discrepancy between geostrophic wind directions and 900 mb wind directions at Crawley in the sectors 020–050° and 130–160° (Appendix A, Table VIII) is an additional complication. This could be simply a local effect on the 900 mb winds measured at Crawley and in that event would introduce an error into the analysis for Heathrow of about −15° in the sector 020–050° and +20° in the sector 130–160°, thus accounting for much of the change of α in different 900 mb wind directions (Figure 12). However Findlater, in an unpublished paper, made a short analysis of Heathrow data for winter months only, using Heathrow geostrophic winds at 0600 and 2100 GMT. The results are very similar to those for stable lapse classes in the present analysis and the changes of α with 900 mb wind direction are assumed to be real changes affecting Heathrow.

2.4.3. *Leuchars.*—At Leuchars the distribution in 900 mb wind direction classes (Figure 4(*d*)) is even more complex than at Heathrow and the pattern varies seasonally and diurnally, the only persistent features being in the west and south-west sectors. A more detailed analysis was attempted, using lapse classes, 900 mb wind speed classes, 900 mb wind directions and seasons simultaneously; but a much longer series of observations is necessary and only very tentative conclusions could be

drawn. Orographic effects may be very critically related to wind direction and smaller or overlapping wind direction sectors are desirable. Supporting data are not presented but the conclusions are listed below.

(i) High values of V_0/V_{900} in the east sector (Figure 4(*d*)) reflect the good exposure seawards but the ratios are smaller than those found by Durst[13] for Gorleston in on-shore winds. The lower values in off-shore winds are generally similar to Durst's.

(ii) The south-west sector shows a very small angle α between the surface wind and the 900 mb wind, regardless of the lapse rate.

(iii) 900 mb winds from north and north-east are frequently associated with veered surface winds.

(iv) Excepting stable lapse classes in winter, almost all surface winds associated with southerly 900 mb winds are markedly backed from the 900 mb direction.

Direction effects (ii), (iii) and (iv) are probably caused by the orography, although sea breezes may contribute towards the veering of surface winds in north to north-east 900 mb winds.

2.5. *Diurnal and annual variations*

2.5.1. *At sea.*—Table III contains mean values of the *p*- and *q*-component ratios for OWS J, treating each of the four seasons and day-time and night-time observations separately. The values were obtained in an earlier analysis which included 900 mb winds between 4 and 9 knots (excluded from this analysis). There are only small seasonal and diurnal changes. Figures 9(*a*) and (*b*) show the mean values of the *p*- and *q*-ratios at the two ocean weather stations for the six lapse classes, separated according to season. There is some tendency for high values of V_0/V_{900} in summer and lower values in winter, which may indicate reduced surface roughness with the lower mean wind speeds in summer (Table IV and para. 2.3.1.), although the accompanying tendency for higher *q*-ratios in summer does not support this.

TABLE III. *Annual and diurnal variation of p- and q-ratios*

		OWS J *			Heathrow			Leuchars		
		p	*q*	No. of obsns	*p*	*q*	No. of obsns	*p*	*q*	No. of obsns
Winter	Day	0·78	0·08	672	0·38	0·16	554	0·31	0·11	348
	Night	0·78	0·07	659	0·26	0·17	542	0·27	0·12	327
Spring	Day	0·75	0·12	682	0·55	0·09	552	0·49	0·08	346
	Night	0·78	0·13	685	0·25	0·16	478	0·32	0·13	292
Summer	Day	0·79	0·16	675	0·58	0·08	494	0·48	0·11	310
	Night	0·77	0·16	671	0·28	0·15	461	0·25	0·17	271
Autumn	Day	0·78	0·13	641	0·47	0·13	518	0·43	0·15	344
	Night	0·78	0·12	638	0·24	0·18	483	0·30	0·14	294
Year	Day	0·78	0·11	2670	0·49	0·12	2118	0·42	0·11	1348
	Night	0·78	0·12	2653	0·26	0·17	1964	0·29	0·14	1184

* Values for OWS J include those on occasions of 900 mb winds between 4 and 9 kt inclusive.

TABLE IV. *Monthly mean wind speeds (knots) at OWS I and J (1948–52)*

	Winter			Spring			Summer			Autumn			
	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Year
OWS I	20·3	22·9	21·5	21·4	20·0	14·9	14·1	13·6	13·4	15·8	18·0	19·6	17·7
OWS J	22·4	22·6	21·2	20·2	17·7	14·7	14·2	13·7	16·1	16·5	20·4	20·3	18·3

2. 5.2. *Over land.*—Table III above shows the marked variation of p- and q-ratios diurnally and, to a lesser extent, seasonally at the two land stations. The variation is due primarily to the differing distribution of lapse rates according to the time of day and season and is demonstrated for Leuchars in Table V as follows. The percentage frequencies of the different lapse classes, given in the first six columns of Table V, were multiplied by the mean annual values $\bar{p}$ and $\bar{q}$ for each class (see bottom of Table V), to yield the weighted means in the last two columns of the table. If the seasonal variations in p and q are entirely due to seasonal variations in lapse-rate frequency, the weighted means $f\bar{p}/100$ and $f\bar{q}/100$ should exactly equal the seasonal means, and they are plotted in Figure 6 against the seasonal means from Table III. The cluster of points near the origin represents q-ratios; the remaining points are p-ratios. All the points lie close to the straight line through the origin bisecting the diagram, which demonstrates the equality of the observed seasonal means from Table III and the weighted means from Table V. Mean p- and q-ratios for six lapse classes and the five 900 mb wind speed classes, for day-time and night-time cases separately, are plotted in Figures 5(*c*)–(*f*). At Heathrow (Figures 5(*c*) and (*d*)) the maximum frequency in the day-time observations appears in 900 mb wind speed class 10–19 kt and lapse class 2 but is transferred to 900 mb wind speed class 20–29 kt and lapse class 4 in the night-time observations. This association of the maximum frequency with stronger 900 mb winds and more stable lapse classes at night is consistent with the diurnal changes of p- and q-ratios shown in Table III for Heathrow and with observed diurnal changes in vertical wind profiles. The diurnal changes of component ratios are not so well marked at Leuchars (Figures 5(*e*) and (*f*)), although there is a noticeable increase at night in the frequencies of lapse classes 3, 4 and 5 occurring with 900 mb wind speeds in the range 20–39 kt.

2.6. *Relationships between V_0/V_{900}, α, p and q*

2.6.1. *At sea.*—At sea, because the surface wind is always a high proportion of the geostrophic wind, the V_0/V_{900} ratio is determined mainly by the magnitude of the p-ratio and α, the angle of backing, is determined mainly by the magnitude of the q-ratio. Figures 3(a), (b) and 5(a) and (b) show that the q-ratio is almost independent of the 900 mb wind speed but varies from almost zero in unstable lapse class 1 to $> 0{\cdot}2$ in the stable lapse classes, with some tendency to decrease in isothermal conditions (paras 2.2.2. and 2.2.3.). The angle α has been shown to depend almost entirely on the lapse class (para. 2.2.4.). Over a relatively smooth sea (900 mb winds 10–19 kt) the p-ratio varies from almost unity in unstable air to about 0·75 in stable air. Over a rough sea (900 mb winds $\geqslant$ 50 kt) the p-ratio varies with lapse class from about 0·75 to 0·5. Therefore the V_0/V_{900} ratio is almost equally dependent on stability and 900 mb wind speed. An interesting relationship occurs in unstable conditions, when the mean angle α approaches zero, while the ratio V_0/V_{900} is significantly less than unity. Taking axes along and across the surface isobars, balanced motion implies:

TABLE V. *Percentage frequencies of lapse classes at Leuchars and derived seasonal and diurnal mean p- and q-ratios*

Lapse class		1	2	3	4	5	6	Number of observations	Weighted means $\frac{f\bar{p}}{100}$	$\frac{f\bar{q}}{100}$
				percentage frequency						
Winter	Day	4	33	37	17	5	3	348	0·34	0·13
	Night	7	8	37	33	10	6	327	0·31	0·14
Spring	Day	39	34	16	10	2	$\frac{1}{3}$	346	0·45	0·09
	Night	0	15	46	27	9	3	292	0·31	0·13
Summer	Day	47	32	14	5	1	$\frac{1}{3}$	310	0·46	0·08
	Night	1	6	53	29	8	4	271	0·30	0·15
Autumn	Day	13	44	34	7	2	$\frac{1}{3}$	344	0·40	0·11
	Night	0	11	44	35	8	3	294	0·30	0·15
Mean annual $\bar{p}$		0·56	0·44	0·32	0·25	0·21	0·13			
Mean annual $\bar{q}$		0·04	0·10	0·15	0·17	0·16	0·05			

$$-fv_n = \frac{1}{\rho} \cdot \frac{\partial T_{z,s}}{\partial z} \quad \ldots (1)$$

$$\text{and} \quad f(v_s - V_G) = \frac{1}{\rho} \cdot \frac{\partial T_{z,n}}{\partial z} \quad \ldots (2)$$

where f is the Coriolis parameter, v_s and v_n are the components of the surface wind along and across the surface isobars and $T_{z,s}$ and $T_{z,n}$ are the shearing stresses along and across the surface isobars. Sheppard *et alii*[12] point out that v_n and the angle α_G, between the surface wind and surface isobars, are determined by the vertical gradient of downwind shear stress $\frac{\partial T_{z,s}}{\partial z}$; also that the difference of surface wind from surface geostrophic wind is determined, for small values of α_G, by the vertical gradient of crosswind shear stress $\frac{\partial T_{z,n}}{\partial z}$. From equation (1), $\frac{\partial T_{z,s}}{\partial z}=0$ when v_n (and α_G) are zero and from equation (2), $\frac{\partial T_{z,n}}{\partial z}=0$ when $v_s=V_G$. Therefore the occurrence in unstable air of $\alpha_G=0$ when v_s $(=V_0)<V_G$ would imply that the vertical gradient of downwind shear stress can become zero, while the vertical gradient of crosswind shear stress is still non-zero. Some care is necessary when interpreting the data because $\alpha_G \neq \alpha$ and $V_G \neq V_{900}$. Findlater demonstrated the existence of a mean westerly thermal associated with 900 mb winds from all directions, the effects of which will only vanish in the mean if all directions are equally likely. The frequencies for unstable lapse class 1 in Tables XIV (*a*) and (*b*) show that westerly winds occur four times as often as easterly winds and it may be shown that V_{900} exceeds V_G by about 4 per cent in the mean. There is also a tendency for the mean thermal wind to back V_{900} slightly with respect to V_G. For these two reasons it is doubtful whether significance can be attached to the overall mean values of $V_0/V_{900}=0{\cdot}91$ and $\alpha=0$. However, when V_{900} speeds lie in the range 30–49 kt, $V_0/V_{900}<0{\cdot}85$ when $\alpha<1°$. The variation

of thermal wind with V_{900} wind speed was not examined but it is unlikely that the thermal wind can account for a reduction of 15 per cent in the V_0/V_{900} ratio and it is probable that $V_0/V_G < 1$ when $\alpha = 0$. Therefore there is some evidence that, in very unstable conditions, the vertical gradient of downwind shear stress can become zero, while the vertical gradient of crosswind shear stress is still non-zero.

2.6.2. *Over land.*—It is difficult to draw conclusions from the land station data because of the doubt about the lapse-rate classification. During the day-time the q-ratios are generally small in unstable air and larger in stable air but the changes are much less regular than at sea. The restricted range of q-values in high 900 mb wind speeds is thought to be a result of increased turbulence modifying the lapse rate in the lower layers and the restriction at night (especially at Heathrow) is probably due to stability in the lowest layers which is not apparent from the mean lapse rate based on temperatures at the surface and 900 mb. (Appendix C.)

In light 900 mb winds the p-ratio varies with lapse rate from about 0·75 to 0·15 at Heathrow and 0·6 to 0·1 at Leuchars, both ranges being smaller in higher 900 mb wind speeds and in all conditions at night. Because the mean p-ratios are smaller and more variable, the angle α varies over a wider range at both land stations than at sea. The analysis for Heathrow of α in 900 mb wind direction classes and lapse classes (Figure 12) shows the general dependence of α on the lapse rate required by Frost's formula for α but it also shows a wide variation in the range of α by lapse class in different 900 mb wind direction classes. The range of α in the north-east and west 900 mb wind direction classes is about 30° and the range in the south to south-east 900 mb wind direction classes is about 60°. The smaller values of α tend to be associated with larger values of V_0/V_{900}.

At Leuchars, although there is the general trend for α to increase and V_0/V_{900} to decrease as the air becomes more stable, the patterns (Figure 13) are very irregular and orographic effects appear to predominate in most sectors. The magnitude of α varies with lapse class from $-20°$ to $+90°$ in the north and north-east sectors but the variation is almost completely suppressed in the south-west sector.

2.7. *Effects of anemometer site and instruments*

The possible effects on the analysis of anemometer site and instrument characteristics are illustrated by reference to changes which took place at Leuchars during the period covered by the analysis. A remote-recording pressure-tube anemometer, 13 metres above ground and 9 metres above nearby buildings with good exposure in all directions, was in use at Leuchars until 31 July 1960. It was replaced from 1 August 1960 to 17 February 1961, by an electric cup anemometer on a 13-metre lattice mast at a different and generally well-exposed site except for winds from the sector 100° to 160°. The forecasting staff at Leuchars considered that a belt of trees near the site caused the electric cup anemometer to under-read by about 30 per cent in this sector. The cup anemometer was transferred to the old pressure-tube anemometer site on 17 February 1961 where the exposure was uninterrupted in all directions. Station records do not indicate serious discrepancies in wind speeds for directions other than 100° to 160° but a comparison of monthly mean wind speeds for Leuchars with those for Auchterhouse, about 12 miles north-west of Leuchars, suggests that both the instrument change on 1 August 1960 and probably the site changes on 1 August 1960 and 17 February 1961 affected the recorded wind speeds (see Table VI). Assuming no changes in the instrument performance at Auchterhouse, the differences in the monthly means indicate that after February 1961 the cup anemometer at Leuchars was recording in the mean about 3 kt higher than the pressure-tube instrument in use before August 1960. Although this change in instrument performance probably has little effect on the broad relationships between V_0 and V_{900} over the whole five-year period, it emphasizes the highly localized nature of such relationships for land stations.

TABLE VI. *Comparison of monthly mean surface wind speeds (knots) at Auchterhouse and Leuchars*

1960	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Auchterhouse	8·6	9·2	12·3	10·7	8·9	8·5	6·9	5·9	7·3	11·6	8·4	7·9	8·9
Leuchars	8·3	7·3	10·1	8·5	6·0	7·1	5·3	6·9	8·2	10·2	7·2	7·9	7·7
Difference	+0·3	+1·9	+2·2	+2·2	+2·9	+2·4	+1·6	−1·0	−0·9	+1·4	+1·2	0·0	+1·2

1961	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Auchterhouse	8·6	10·0	12·0	9·2	7·6	9·4	8·1	8·1	7·2	9·5	7·2	7·7	8·7
Leuchars	8·8	10·6	13·2	8·8	8·7	11·2	8·9	9·5	8·7	10·9	8·1	7·0	9·5
Difference	−0·2	−0·6	−1·2	+0·4	−1·1	−1·8	−0·8	−1·4	−1·5	−1·4	−0·9	+0·7	−0·8

2.8. *The general effects of topography*

Wind roses based on 5 to 10 years of observations from four to eight times daily and showing frequencies of surface winds in twelve 30° sectors have been compiled for 37 stations, to accompany aerodrome weather diagrams. A selection of these are plotted on a topographical map of the British Isles in Figure 10 and provide clear evidence of orographic effects at most stations. The mean pressure distribution yields a maximum of south-westerly winds but the maximum at individual stations may vary through a wide range of directions. For example its occurrence from 270° at Rhoose, 240° at Filton (near Bristol), 210° at Pershore and 180° with a secondary maximum from 300–330° at Liverpool, is very suggestive of airflow round the Welsh mountains. The maxima from 120°–150° and 000°–030° at Dishforth, in the Vale of York and 150°–180° and 300°–330° at Aberdeen, all in sectors which normally display minima, are especially striking.

2.9. *Conclusions*

2.9.1. *The relationships at sea.*—The mean values of α and V_0/V_{900} are 8° and 0·8. α is affected most by the temperature lapse rate and varies from zero in very unstable air to about 25° in very stable air. There is a small increase of α with increasing 900 mb wind speed, amounting to about 3° over the whole 900 mb wind speed range, but in very unstable air the change with 900 mb wind speed is completely suppressed until speeds approach 50 kt. The associated V_0/V_{900} ratios depend almost equally on both temperature lapse rate and 900 mb wind speed, decreasing with increasing 900 mb wind speed and with increasing stability until the temperature lapse rate approaches zero. The range is from 1·0 in unstable air and light winds to about 0·5 in stable conditions and strong winds. The changes in α and V_0/V_{900} which take place with 900 mb wind direction are probably caused by a thermal wind component in the surface–900 mb layer and also by correlation of the temperature lapse rate with wind direction. Diurnal and seasonal changes are small. There is some evidence that sea surface roughness varies linearly with 900 mb wind speed until some high wind speed, probably exceeding 50 kt, is reached; after which the roughness decreases. In very unstable conditions α is observed to become zero while $V_0/V_{900} < 1$ and it is inferred that the vertical gradient of downwind shear stress may become zero while the vertical gradient of crosswind shear stress is still non-zero.

2.9.2. *The relationships over the land.*—The mean values of α and V_0/V_{900} are 20° and 0·4. The value of α varies with temperature lapse rate from zero in very unstable conditions to about 45° in stable air. As the 900 mb wind speed increases there is a small increase in α at Heathrow but a small decrease at Leuchars. V_0/V_{900} varies from 0·7 in very unstable air to 0·2 in stable air. There is no significant change with 900 mb wind speed. The effects of lapse rate on both α and V_0/V_{900} can be completely obscured by the effects of orography and surface roughness both of which may vary greatly in different directions at a land station. Data for 14 stations throughout the British Isles show the importance of orography at considerable distances from each station and α and V_0/V_{900} are found to vary considerably with wind direction, even where the local exposure may be good for up to 16 km in all directions as at Heathrow. At stations such as Leuchars, where the immediate locality is strongly contoured, the effects of orography may be critically dependent on the 900 mb wind direction and cannot be fully investigated without a long series of observations and a direction analysis in small or overlapping wind sectors. The directional analyses are complicated by the thermal wind component which could not be isolated from the other directional effects due to orography and surface roughness. Because of the large effects due to orography and surface roughness it is difficult to draw conclusions about the relationships between 900 mb and surface winds which have general applications over land areas. Large variations occur diurnally and seasonally but are shown to be caused by temperature lapse-rate changes. The temperature lapse-rate classification, based on temperatures at the surface and 900 mb only, is not sufficiently detailed for land areas and more information is required about the temperature structure in a shallow layer near the ground.

3. A POSSIBLE FORECASTING TECHNIQUE

3.1. Useful associations of V_0/V_{900} and α with the temperature lapse-rate and 900 mb wind speed at sea have been established (Figures 11(*a*) and (*b*)) and provide the basis for a forecasting technique. The first step in the technique is to estimate the wind which would blow under the influence of the forecast sea-level isobaric pattern, if the sea surface were frictionless. This estimate must be based either on the forecast geostrophic wind or, if the indicated air trajectory is strongly curved, on the forecast gradient wind. In some circumstances the forecaster may decide to apply corrections if large changes are expected in the surface pressure field at the forecast time. The next step is to forecast the temperature lapse rate in the lowest layers. Diurnal changes of temperature lapse rate are small at sea and, in comparison with the problem over land, it is relatively easy to forecast the temperature lapse rate from a representative temperature sounding. The technique may be applied through diagrams such as Figures 11(*a*) and (*b*) or using the smoothed values in Table VII

TABLE VII. *Smoothed values of V_0/V_{900} and α for classes of 900 mb wind speed and lapse rate—OWS I and J*

900 mb wind speed class (kt)	10–19		20–29		30–39		40–49		⩾50	
Lapse class	V_0/V_{900}	α°	V_0/V_{900}	α°	V_0/V_{900}	α°	V_0/V_{900}	α°	V_0/V_{900}	α°
1	0·97	0	0·91	0	0·85	0	0·81	0	0·78	0
2	0·90	5	0·84	5	0·79	5	0·76	5	0·74	5
3	0·85	10	0·77	12	0·71	15	0·67	12	0·64	10
4	0·80	17	0·72	20	0·66	20	0·61	22	0·59	20
5	0·75	15	0·68	18	0·63	20	0·58	20	0·54	25

which are based on the data from both ocean weather stations. There are insufficient observations in lapse class 6 to indicate the effect of wind speed. The means for all observations in this lapse class are $V_0/V_{900}=0{\cdot}74$ and $\alpha=24°$.

3.2. It is not possible to lay down a technique for land stations generally because, although the general effect of lapse class on V_0/V_{900} and α is still detectable, it is sometimes overwhelmed by complex effects of 900 mb wind speed, 900 mb wind direction and diurnal changes related to local orography. Also, it is very much more difficult to forecast the fine structure of the low-level temperature lapse rate over the land than over the sea. Little further progress can be expected until the effects of the fine structure of the temperature lapse rate have been investigated and until sufficiently long data series are available to sustain more complex analyses using wind speeds, temperature lapse rate and overlapping wind direction sectors simultaneously. Meanwhile some general guidance can be obtained from the data in Figures 5(*c*)–(*f*), 12, 13 and Tables XIII(*c*)–(*f*) and XIV (*c*) and (*d*).

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BIBLIOGRAPHY

1. FROST, R.; Atmospheric turbulence. *Q. Jl R. met. Soc., London*, **74**, 1948, p. 316.
2. MARSHALL, W. A. L.; Comparison of the wind recorded by anemograph with the geostrophic wind. *Prof. Notes met. Off., London*, No. 108, 1954.
3. WILSON, H. P.; The influence of stability on surface wind behaviour. Meteorological Branch, Department of Transport, Toronto, 1959, Circular 3266.
4. WILSON, H. P.; Surface wind relationships from Frost's power law. Meteorological Branch, Department of Transport, Toronto, 1961, Circular 3475.
5. WILSON, H. P.; A comparison of theoretical and actual surface wind data. Meteorological Branch, Department of Transport, Toronto, 1961, Circular 3518.
6. JEHN, K. H. and DURIE, S. J.; Boundary-layer-wind maxima and associated temperature distributions as observed on the 1400 foot television tower near Dallas, Texas 1961–1962. Austin, Texas, University of Texas Electrical Engineering Research Laboratory, Report 4-09, AFCRL-63-738, 1963.
7. THUILLIER, R. H. and LAPPE, U. O.; Wind and temperature profile characteristics from observations on a 1400 ft tower. *J. appl. Met., Lancaster, Pa.*, **3**, 1964, p. 299.
8. WESTWATER, F. L.; Wind structure over the sea. *Q. Jl R. met. Soc., London*, **69**, 1943, p. 207.
9. BRADBURY, N.; Wind. Handbook of weather forecasting, 1960. (Unpublished, copy available in Meteorological Office Library.)
10. CHARNOCK, H.; Wind stress on a water surface. *Q. Jl R. met. Soc., London*, **81**, 1955, p. 639.
11. BOYDEN, C. J.; Relationships between sea-level isobars and the wind speed at 900 metres. *Met. Mag., London*, **92**, 1963, p. 101.
12. SHEPPARD, P. A., CHARNOCK, H. and FRANCIS, J. R. D.; Observations of the westerlies over the sea. *Q. Jl R. met. Soc., London*, **78**, 1952, p. 563.
13. DURST, C. S.; Relation of surface winds to pressure gradients. *Met. Mag., London*, **78**, 1949, p. 157.
14. GORDON, A. H.; The ratio between observed velocities of the wind at 50 feet and 2000 feet over the North Atlantic Ocean. *Q. Jl R. met. Soc., London*, **76**, 1950, p. 344.

Appendix A—COMPARISON OF 900 MB AND GEOSTROPHIC WINDS

Although numerous investigations have been made into wind profiles near the earth's surface, few incorporate the geostrophic wind and few are capable of direct application to the problem of forecasting the surface wind. Geostrophic winds are neither calculated nor measured as a routine and their extraction in retrospect is very tedious; nor can values be relied on unless there is a close network of surface pressure reports. Actual winds for a pressure height of 900 mb, measured by radar during radiosonde ascents, are readily available from climatological punched cards and were adopted instead of geostrophic winds.

There are several objections to using the 900 mb wind. It is a mean wind measured over a time interval of two or three minutes and applies to a layer 800 to 1200 m thick, the mean height of which varies from about 400 to 1200 m near the British Isles. When the 900 mb surface lies below 600 m the reported mean wind applies to a layer starting at the earth's surface and therefore must include all the effects of surface friction. Boyden[11] investigated relationships between mean sea-level isobars and winds at 900 m and found that, for Crawley (145 m above MSL) with steady straight isobars, the difference between geostrophic winds measured from isobars and 900 m winds observed during radiosonde ascents increased as the geostrophic wind speed increased. At Crawley, the 900 m wind is the mean wind for a layer 800 to 1200 m thick, starting at 350 m above ground, and Boyden's results indicate that surface friction must have a significant effect above 350 m whenever geostrophic winds exceed about 25 kt. A further complication is the thermal wind (or change of geostrophic wind with height), the existence of which was demonstrated by Sheppard *et alii*.[12] Findlater in an unpublished paper, using data for the eastern North Atlantic, calculated a mean value for the thermal wind in the 1000 to 900 mb layer of about 255° 2 kt and also showed that this value applied whatever the direction of the surface wind. The latter fact is important when interpreting the behaviour of the 900 mb and surface wind relationship at sea. Findlater's mean value was confirmed by using the mean 1000–900 mb thicknesses at OWS I and J and radiosonde stations Shanwell and Crawley to calculate the mean westerly and northerly thermal wind components. The two components, when added vectorially, yield a thermal wind of 248° 1·7 kt.

Although 900 mb winds were used as a convenient alternative to geostrophic winds, it was intended that they should be compared with calculated geostrophic winds as the latter became available from a separate computation programme based on surface pressures from a close network of reporting stations. So far, geostrophic wind data are only available for the London area. Tables VIII and IX show comparisons of 900 mb winds with geostrophic winds for Crawley and are broadly in accordance with Boyden's findings. In Table VIII, 29 of the 10° sectors show differences of 10° or less but there is a hint of larger systematic differences in the sectors 020–050° and 130°–160°. The correspondence between geostrophic and 900 mb wind speeds (Table IX) is good in the low speed ranges but the mean 900 mb winds fall short of geostrophic speeds in the higher ranges by amounts which exceed Boyden's figures for steady straight isobars. Much of the discrepancy between 900 mb wind speed and geostrophic wind speed is explained by the intrusion of surface friction effects into the 900 mb layer; the residue is probably due to cyclonic curvature of the airflow, which is likely to occur most frequently with strong 900 mb winds.

Summary

Relationships between 900 mb winds and surface winds may be complicated by the following factors:

(i) The intrusion of surface friction effects into the 900 mb layer,

(ii) Changes of geostrophic wind with height, and

(iii) Departure from geostrophic conditions of flow.

TABLE VIII. *Comparison of 900 mb and geostrophic wind directions, in 10° sectors, at Crawley for 25 months (Nov.–Mar. 1957–61)*

Geostrophic wind direction	000	010	020	030	040	050	060	070	080	090	100	110	120	130	140	150	160	170
900 mb wind direction	350	000	000	020	030	030	060	050	090	090	100	110	130	160	160	170	170	170
Number of observations	8	19	11	12	21	23	17	25	13	12	10	10	15	5	7	4	10	9
Difference, tens of degrees	−1	−1	−2	−1	−1	−2	0	−2	+1	0	0	0	+1	+3	+2	+2	+1	0

Geostrophic wind direction	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
900 mb wind direction	190	180	200	220	210	230	220	240	270	280	290	290	300	320	320	320	330	340
Number of observations	7	20	17	26	33	36	32	37	35	18	16	22	22	15	21	18	12	18
Difference, tens of degrees	+1	−1	0	+1	−1	0	−2	−1	+1	+1	+1	0	0	+1	0	−1	−1	−1

TABLE IX. *Comparison of 900 mb and geostrophic wind speeds (knots) at Crawley for 25 months (Nov.–Mar., 1957–61)*

Geostrophic speed range	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69
Mean 900 mb speed range	13	16	21	25	29	31	34	38	42	41	44	45
Number of observations	102	111	107	90	74	48	40	30	21	9	6	6
Mean difference (knots)	+1	−1	−1	−2	−3	−6	−8	−9	−10	−15	−17	−22

Appendix B—ON LOCATION

Data for OWS I and J were selected to represent conditions at sea and also because the relationship between surface and 900 mb winds might prove simpler in the absence of orographical effects and directional changes of surface roughness. Two land sites were selected. Surface winds at London (Heathrow) Airport were compared with 900 mb winds at Crawley and surface winds at Leuchars were compared with 900 mb winds at Shanwell. Crawley is 39 km from Heathrow and Shanwell

5 km from Leuchars. The anemometer exposures at both stations are good, although some complications occurred temporarily at Leuchars and are discussed in para. 2.7. At Heathrow there are no major orographic features within 16 km of the site but at Leuchars the orography is known to exert considerable influence on winds from some sectors and complications may also occur due to land and sea breezes. The effect on the analysis of using surface and 900 mb winds from different locations was tested by comparing geostrophic winds at Crawley and geostrophic winds at Heathrow with 900 mb winds at Crawley. The results are not produced in full but standard errors and correlation coefficients are given in Table X.

TABLE X. *Comparison of geostrophic and 900 mb winds at Crawley and Heathrow for 25 months (Nov.–Mar., 1957–61)*

	Standard error	Correlation coefficient
Geostrophic, Crawley–900 mb, Crawley,		
direction	4·32°	0·94
speed	9·28 kt	0·75
Geostrophic, Heathrow–geostrophic, Crawley,		
direction	2·85°	0·97
speed	6·57 kt	0·91
Geostrophic, Heathrow–900 mb, Crawley,		
direction	4·36°	0·94
speed	8·59 kt	0·79

Summary

The effect on the analysis of using upper winds at Crawley for comparison with surface winds at Heathrow is probably negligible. However, the difference in location may involve important temperature lapse rate changes in the lowest layers near the ground, the effects of which are discussed in Appendix C.

Appendix C—ON LAPSE CLASS

Data from instruments exposed on high masts (Jehn and Durie,[6] Thuiller and Lappe[7]) suggest that it is the temperature lapse rate in the first 300 m above ground which is most closely associated with the vertical wind profile up to 900 mb. These new data raised doubts about the relevancy of the lapse class as defined above and three months of plotted tephigrams for OWS I, Leuchars and Crawley were inspected with the following results:

OWS I.—The mean temperature lapse rate from the surface to 900 mb was usually typical of the temperature lapse rate in the lower layers. A lapse class based on the lowest layers would have led to reclassification on about half the cases examined but the changes showed no bias and were nearly all confined to adjacent lapse classes.

Shanwell.—Low-level inversions occurred frequently at night and were not reflected in the mean temperature lapse rate from the surface to 900 mb.

Crawley.—Night-time low-level inversions occurred less often than at Shanwell—possibly because cold air tends to drain away from the Crawley site which is on a low ridge—but should be more frequent at Heathrow where the night-time low-cloud cover, especially in summer, is less than at Shanwell.

Summary

Although the lapse classification based on the temperature difference between the surface and 900 mb is adequate at sea this may not be so over land where a more sophisticated classification may be necessary.

Appendix D—ON CORRELATION OF PARAMETERS

The unavoidable combination of classes, described at para. 1.5., may obscure the full effect of the classifying parameter if it is correlated with others temporarily discarded. For example, mechanical turbulence affects the lapse rate in the lowest layers and lapse rate must be correlated with 900 mb wind speed. Data for OWS I and Heathrow were tested for such correlation by extracting for south-westerly 900 mb wind directions, the frequencies of each lapse class within each 900 mb wind speed class. These frequencies were expressed as percentages for each lapse class and weighted to eliminate the bias due to differences in the frequency of occurrence within each 900 mb speed class. The weighted frequencies (Table XI) show no established correlation for OWS I but there is a distinct tendency in the data for Heathrow towards both stable and unstable lapse classes at low wind speed and towards the neutral lapse class 3 at high wind speeds. A similar test of 900 mb wind direction and lapse-class frequencies for 900 mb wind speeds between 20 and 29 kt (Table XII) showed that, in the OWS I data, unstable lapse classes were associated with northerly winds and stable lapse classes with southerly winds. Directional changes of surface roughness, orography and possibly anemometer exposure must be expected at a land station and it is not surprising that correlation of lapse class with 900 mb wind direction does not show in the Heathrow data.

TABLE XI. *Weighted frequencies of lapse classes in 900 mb wind speed classes, for 900 mb direction class south-west*

	OWS I						London (Heathrow) Airport					
Speed class	Lapse class						Lapse class					
(knots)	1	2	3	4	5	6	1	2	3	4	5	6
10–19	5·4	8·1	8·1	6·7	3·0	6·7	5·8	4·6	1·3	2·5	3·9	4·9
20–29	6·3	8·3	7·1	6·0	6·8	5·0	3·1	2·9	2·6	3·3	3·3	1·8
30–39	9·8	7·0	6·7	7·9	11·5	16·9	0·7	1·8	4·1	2·8	1·3	2·8
40–49	8·5	7·4	6·4	8·5	8·5	0	0	0·9	4·1	2·9	2·9	1·5
⩾50	8·5	3·9	11·6	11·4	6·8	0	0	1·6	5·5	2·3	0	0

TABLE XII. *Weighted frequencies of lapse classes in 900 mb wind direction classes, for 900 mb wind speed class 20–29 knots*

	OWS I						London (Heathrow) Airport					
Direction	Lapse class						Lapse class					
class	1	2	3	4	5	6	1	2	3	4	5	6
N	9·3	7·9	4·3	0·7	1·4	0	3·3	3·7	5·0	3·3	1·3	2·1
NE	9·2	7·0	4·2	4·9	0	0	8·5	5·4	3·8	3·1	3·8	1·9
E	6·9	6·9	5·2	6·9	7·8	10·4	4·4	2·8	3·3	2·8	7·2	10·6
SE	2·1	5·7	7·8	15·0	6·4	8·6	5·6	2·6	3·7	3·2	5·6	8·6
S	4·0	4·8	10·6	7·9	7·9	11·0	5·0	2·1	3·9	3·6	5·0	7·5
SW	4·9	6·2	7·5	7·5	8·8	2·0	2·7	3·9	3·7	3·7	3·5	1·9
W	6·9	6·9	4·7	6·1	8·1	11·2	2·2	4·2	3·1	4·0	3·5	3·4
NW	10·1	6·9	5·8	2·6	3·7	3·1	2·9	3·7	3·4	4·5	2·6	1·8

Summary

Correlation occurs between 900 mb wind speed and lapse class over land and between 900 mb wind direction and lapse class over the sea.

TABLE XIII. *Mean values of p, q, V_0/V_{900} and α for five 900 mb wind speed classes and six lapse classes. (Standard deviations of p and q shown in parentheses; number of observations, comprising each group of four means, shown below mean V_0/V_{900})*

(a) OWS I (day-time and night-time)

900 mb wind speed class	10–19 kt				20–29 kt				30–39 kt				40–49 kt				⩾ 50 kt				All speeds			
Lapse class	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°
1	0·98	0·02	0·98	1	0·91	−0·01	0·91	−1	0·86	0·02	0·87	1	0·83	0·02	0·83	1	0·79	0·06	0·80	4	0·89	0·01	0·89	1
	(0·31)	(0·34)	137		(0·17)	(0·24)	196		(0·12)	(0·17)	188		(0·11)	(0·15)	93		(0·10)	(0·13)	38		(0·19)	(0·23)	652	
2	0·92	0·06	0·92	4	0·85	0·06	0·85	4	0·81	0·06	0·81	4	0·77	0·06	0·77	5	0·75	0·07	0·75	6	0·85	0·06	0·85	4
	(0·30)	(0·33)	901		(0·18)	(0·23)	967		0·15)	(0·17)	665		(0·12)	(0·14)	328		(0·12)	(0·13)	121		(0·22)	(0·24)	2982	
3	0·85	0·14	0·87	9	0·77	0·18	0·79	13	0·69	0·17	0·71	13	0·67	0·13	0·68	11	0·64	0·13	0·65	11	0·75	0·16	0·77	12
	(0·33)	(0·40)	374		(0·19)	(0·24)	402		(0·17)	(0·20)	274		(0·16)	(0·16)	141		(0·11)	(0·13)	106		(0·24)	(0·28)	1297	
4	0·83	0·23	0·86	16	0·71	0·22	0·75	17	0·64	0·21	0·67	18	0·60	0·23	0·65	21	0·58	0·20	0·62	19	0·70	0·22	0·73	17
	(0·34)	(0·44)	116		(0·20)	(0·24)	141		(0·15)	(0·15)	112		(0·10)	(0·14)	43		(0·10)	(0·11)	37		(0·24)	(0·28)	449	
5	0·76	0·17	0·78	13	0·67	0·19	0·70	17	0·63	0·19	0·66	17	0·59	0·18	0·61	17	0·52	0·23	0·57	24	0·66	0·19	0·69	16
	(0·43)	(0·29)	30		(0·22)	(0·25)	44		(0·12)	(0·16)	42		(0·12)	(0·11)	20		(0·07)	(0·11)	5		(0·26)	(0·22)	141	
6	0·88	0·51	1·01	30	0·73	0·29	0·79	22	0·75	0·16	0·76	12	0·65	0·25	0·72	21	0·52	0·20	0·56	21	0·77	0·33	0·84	23
	(0·21)	(0·34)	11		(0·22)	(0·19)	16		(0·10)	(0·10)	6		—	—	1		—	—	1		(0·21)	(0·27)	35	
All classes	0·90	0·10	0·90	6	0·82	0·10	0·83	7	0·77	0·10	0·78	7	0·74	0·09	0·74	7	0·69	0·11	0·70	9	0·81	0·10	0·82	7
	(0·32)	(0·36)	1569		(0·19)	(0·24)	1766		(0·17)	(0·18)	1287		(0·15)	(0·15)	626		(0·15)	(0·14)	308		(0·24)	(0·26)	5556	

(b) OWS J (day-time and night-time)

900 mb wind speed class	10–19 kt				20–29 kt				30–39 kt				40–49 kt				⩾ 50 kt				All speeds			
Lapse class	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°
1	0·96	0·01	0·96	1	0·89	−0·01	0·89	−1	0·83	0·02	0·83	1	0·82	0·00	0·82	0	0·71	0·17	0·73	13	0·87	0·01	0·94	1
	(0·37)	(0·30)	81		(0·18)	(0·22)	101		(0·14)	(0·19)	108		(0·11)	(0·13)	55		(0·21)	(0·19)	17		(0·23)	(0·22)	362	
2	0·88	0·07	0·88	4	0·82	0·08	0·83	6	0·77	0·07	0·77	5	0·73	0·05	0·74	4	0·72	0·07	0·72	6	0·81	0·07	0·82	5
	(0·32)	(0·31)	680		(0·21)	(0·24)	733		(0·15)	(0·18)	519		0·17)	(0·17)	246		(0·12)	(0·13)	113		(0·24)	(0·24)	2291	
3	0·82	0·15	0·83	10	0·73	0·14	0·75	11	0·67	0·19	0·70	15	0·65	0·14	0·66	12	0·60	0·13	0·61	13	0·73	0·15	0·75	12
	(0·37)	(0·41)	349		(0·23)	(0·23)	399		(0·16)	(0·18)	283		(0·16)	(0·14)	129		(0·10)	(0·17)	81		(0·27)	(0·27)	1241	
4	0·73	0·23	0·77	18	0·65	0·25	0·69	21	0·60	0·23	0·64	21	0·53	0·24	0·58	24	0·56	0·19	0·59	19	0·63	0·23	0·67	20
	(0·38)	(0·47)	127		(0·26)	(0·27)	208		(0·15)	(0·19)	153		(0·21)	(0·12)	87		(0·08)	(0·10)	57		(0·26)	(0·27)	632	
	0·71	0·22	0·74	17	0·60	0·22	0·64	21	0·59	0·20	0·62	19	0·51	0·23	0·56	24	0·44	0·26	0·51	31	0·61	0·22	0·64	20
	(0·32)	(0·45)	48		(0·19)	(0·20)	56		(0·15)	(0·13)	41		(0·09)	(0·11)	24		(0·28)	(0·15)	10		(0·23)	(0·27)	179	
6	0·55	0·23	0·60	23	0·59	0·31	0·66	27	0·46	0·31	0·55	33	0·55	0·18	0·58	18	No observations				0·55	0·26	0·61	25
	(0·22)	(0·17)	8		(0·17)	(0·20)	9		(0·09)	(0·08)	3		(0·09)	(0·17)	3						(0·18)	(0·23)	23	
All classes	0·84	0·11	0·85	7	0·77	0·12	0·78	9	0·72	0·12	0·73	9	0·68	0·11	0·69	9	0·64	0·13	0·65	11	0·76	0·11	0·77	9
	(0·35)	(0·36)	1293		(0·23)	(0·25)	1506		(0·17)	(0·19)	1107		(0·19)	(0·17)	544		(0·15)	(0·15)	278		(0·26)	(0·26)	4728	

TABLE XIII (*continued*)

(*c*) *Heathrow* (*day-time*)

900 mb wind speed class	10–19 kt				20–29 kt				30–39 kt				40–49 kt				⩾ 50 kt				All speeds			
Lapse class	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°
1	0·76 (0·22)	−0·05 (0·23)	0·76 68	−4	0·65 (0·13)	0·06 (0·17)	0·65 24	5	0·48 (0·06)	0·03 (0·06)	0·48 4	4	No observations				No observations				0·72 (0·21)	0·02 (0·22)	0·72 96	−2
2	0·63 (0·27)	0·05 (0·27)	0·63 464	5	0·56 (0·16)	0·06 (0·16)	0·57 267	6	0·49 (0·11)	0·07 (0·13)	0·49 105	8	0·48 (0·09)	0·08 (0·10)	0·49 19	9	0·34 (0·22)	0·10 (0·06)	0·36 5	16	0·59 (0·23)	0·06 (0·22)	0·59 860	6
3	0·47 (0·31)	0·16 (0·27)	0·50 270	19	0·43 (0·16)	0·15 (0·15)	0·45 259	19	0·40 (0·12)	0·13 (0·12)	0·43 157	18	0·41 (0·08)	0·13 (0·09)	0·43 57	18	0·42 (0·06)	0·10 (0·07)	0·43 15	13	0·44 (0·22)	0·15 (0·19)	0·46 758	19
4	0·37 (0·28)	0·26 (0·27)	0·45 106	35	0·37 (0·16)	0·21 (0·16)	0·43 115	29	0·36 (0·13)	0·17 (0·11)	0·40 55	25	0·29 (0·11)	0·11 (0·14)	0·31 22	21	0·35 (0·03)	0·15 (0·06)	0·39 6	23	0·37 (0·20)	0·21 (0·20)	0·42 304	30
5	0·21 (0·30)	0·28 (0·25)	0·35 32	53	0·35 (0·19)	0·22 (0·15)	0·41 23	32	0·34 (0·09)	0·21 (0·11)	0·40 8	32	0·33 (0·10)	0·19 (0·04)	0·38 4	30	0·35 (0·09)	0·19 (0·10)	0·40 2	28	0·28 (0·24)	0·24 (0·20)	0·37 69	41
6	0·34 (0·34)	0·24 (0·26)	0·41 19	35	0·34 (0·10)	0·24 (0·14)	0·41 7	35	0·20 (0·14)	0·18 (0·05)	0·27 4	42	0·35 —	0·20 —	0·41 1	30	No observations				0·32 (0·28)	0·23 (0·21)	0·39 31	36
All classes	0·55 (0·31)	0·11 (0·28)	0·56 959	11	0·47 (0·18)	0·13 (0·17)	0·49 695	15	0·42 (0·13)	0·12 (0·13)	0·44 333	16	0·39 (0·11)	0·12 (0·10)	0·41 103	17	0·39 (0·11)	0·12 (0·08)	0·40 28	17	0·49 (0·24)	0·12 (0·22)	0·51 2118	14

(*d*) *Heathrow* (*night-time*)

900 mb wind speed class	10–19 kt				20–29 kt				30–39 kt				40–49 kt				⩾ 50 kt				All speeds			
Lapse class	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°	*p*	*q*	V_0/V_{900}	α°
1	0·26 (0·14)	0·05 (0·15)	0·26 4	11	0·33 (0·21)	0·12 (0·16)	0·35 12	20	0·21 (0·06)	0·18 (0·08)	0·29 4	41	0·32 (0·04)	0·11 (0)	0·34 2	19	0·34 —	0·09 —	0·35 1	15	0·29 (0·17)	0·12 (0·14)	0·32 23	23
2	0·15 —	0·23 —	0·27 1	57	0·23 (0·09)	0·18 (0·09)	0·29 3	38	0·31 (0·08)	0·15 (0·03)	0·35 3	26	0·41 (0·05)	0·09 (0·10)	0·42 6	12	0·35 (0)	0·17 (0·04)	0·39 2	26	0·33 (0·11)	0·14 (0·09)	0·36 15	23
3	0·32 (0·21)	0·16 (0·18)	0·36 122	27	0·29 (0·15)	0·16 (0·11)	0·33 168	29	0·32 (0·11)	0·14 (0·10)	0·35 161	24	0·35 (0·11)	0·14 (0·07)	0·37 53	22	0·36 (0·13)	0·08 (0·11)	0·37 21	13	0·31 (0·15)	0·15 (0·13)	0·35 525	26
4	0·25 (0·18)	0·17 (0·18)	0·30 352	34	0·24 (0·13)	0·17 (0·10)	0·29 358	35	0·27 (0·11)	0·17 (0·07)	0·32 170	32	0·30 (0·09)	0·17 (0·08)	0·34 39	29	0·35 (0·04)	0·09 (0·04)	0·36 7	14	0·25 (0·15)	0·17 (0·13)	0·30 926	34
5	0·21 (0·21)	0·20 (0·23)	0·29 173	44	0·20 (0·14)	0·17 (0·11)	0·26 102	40	0·25 (0·13)	0·16 (0·08)	0·30 35	33	0·26 (0·09)	0·16 (0·10)	0·30	32	No observations				0·21 (0·18)	0·18 (0·19)	0·28 317	41
6	0·21 (0·24)	0·21 (0·20)	0·30 90	45	0·20 (0·15)	0·18 (0·12)	0·27 51	42	0·17 (0·14)	0·12 (0·10)	0·21 16	35	0·11 —	0·10 —	0·15 1	42	No observations				0·21 (0·20)	0·19 (0·17)	0·28 158	42
1 classes	0·25 (0·20)	0·18 (0·20)	0·30 742	36	0·24 (0·14)	0·17 (0·11)	0·29 694	35	0·29 (0·12)	0·15 (0·09)	0·33 389	27	0·33 (0·11)	0·15 (0·08)	0·36 108	25	0·35 (0·11)	0·09 (0·10)	0·36 31	14	0·26 (0·17)	0·17 (0·15)	0·31 1964	33

TABLE XIII (*continued*)

(*e*) *Leuchars* (*day-time*)

900 mb wind speed class	10–19 kt				20–29 kt				30–39 kt				40–49 kt				⩾ 50 kt				All speeds			
Lapse class	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°
1	0·57 (0·31)	0·02 (0·32)	0·57 192	2	0·59 (0·15)	0·05 (0·21)	0·59 103	5	0·59 (0·12)	0·06 (0·17)	0·59 36	6	0·63 (0·08)	−0·04 (0·06)	0·63 6	−4	0·48 (0·02)	0·07 (0·04)	0·49 3	8	0·57 (0·25)	0·03 (0·27)	0·58 340	3
2	0·41 (0·35)	0·12 (0·30)	0·43 199	16	0·45 (0·17)	0·12 (0·20)	0·47 141	15	0·46 (0·16)	0·09 (0·14)	0·47 91	11	0·48 (0·12)	0·06 (0·12)	0·49 41	7	0·45 (0·05)	0·05 (0·09)	0·46 10	6	0·44 (0·26)	0·11 (0·23)	0·45 482	14
3	0·31 (0·32)	0·20 (0·30)	0·37 139	33	0·33 (0·22)	0·15 (0·17)	0·36 102	25	0·36 (0·13)	0·12 (0·12)	0·38 63	18	0·42 (0·14)	0·11 (0·16)	0·43 35	15	0·41 (0·09)	0·09 (0·10)	0·42 6	12	0·34 (0·25)	0·16 (0·22)	0·37 345	25
4	0·25 (0·32)	0·21 (0·28)	0·33 56	40	0·31 (0·25)	0·19 (0·17)	0·37 51	32	0·34 (0·19)	0·13 (0·16)	0·36 17	21	0·30 (0·08)	0·16 (0·15)	0·34 7	28	0·36 (0·13)	0·05 (0·05)	0·36 3	8	0·29 (0·27)	0·19 (0·22)	0·35 134	33
5	0·12 (0·28)	0·20 (0·21)	0·23 12	59	0·29 (0·22)	0·24 (0·17)	0·38 11	40	0·32 (0·10)	0·12 (0·13)	0·34 8	21	0·06 —	0·09 —	0·11 1	124	0·27 —	0·10 —	0·29 1	−20	0·22 (0·24)	0·18 (0·19)	0·29 33	39
6	0·07 (0·17)	0·13 (0·16)	0·14 5	62	0·03 (0·06)	−0·02 (0·04)	0·04 3	−34	0·17 (0·19)	0·15 (0·25)	0·23 5	41	0·06 —	0·24 —	0·25 1	76	No observations				0·10 (0·16)	0·11 (0·19)	0·15 14	48
All classes	0·41 (0·35)	0·12 (0·31)	0·43 603	16	0·43 (0·22)	0·12 (0·20)	0·45 411	16	0·43 (0·17)	0·10 (0·15)	0·44 220	13	0·44 (0·16)	0·09 (0·13)	0·45 91	12	0·43 (0·10)	0·06 (0·09)	0·43 23	8	0·42 (0·28)	0·11 (0·24)	0·44 1348	15

(*f*) *Leuchars* (*night-time*)

900 mb wind speed class	10–19 kt				20–29 kt				30–39 kt				40–49 kt				⩾ 50 kt				All speeds			
Lapse class	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°
1	0·29 (0·08)	0·21 (0·44)	0·36 6	36	0·36 (0·20)	0·08 (0·10)	0·37 6	13	0·34 (0·12)	0·12 (0·16)	0·36 7	19	0·38 (0·08)	0·21 (0·08)	0·43 2	29	0·43 (0)	0·06 (0·04)	0·43 3	8	0·35 (0·42)	0·13 (0·25)	0·37 24	20
2	0·43 (0·21)	0·07 (0·21)	0·44 30	9	0·38 (0·14)	0·09 (0·16)	0·39 36	13	0·43 (0·18)	0·11 (0·16)	0·45 28	14	0·43 (0·32)	0·11 (0·08)	0·43 13	14	0·44 (0·14)	0·07 (0·08)	0·45 9	9	0·42 (0·19)	0·09 (0·16)	0·43 116	12
3	0·29 (0·22)	0·14 (0·20)	0·32 173	26	0·30 (0·32)	0·14 (0·15)	0·33 167	25	0·31 (0·13)	0·13 (0·11)	0·34 123	23	0·37 (0·11)	0·11 (0·12)	0·39 52	17	0·46 (0·09)	0·08 (0·08)	0·47 14	10	0·31 (0·18)	0·13 (0·16)	0·34 529	23
4	0·22 (0·25)	0·19 (0·21)	0·29 154	41	0·24 (0·15)	0·16 (0·14)	0·29 131	34	0·27 (0·13)	0·13 (0·11)	0·30 60	26	0·30 (0·12)	0·08 (0·09)	0·31 19	15	0·31 (0·08)	0·08 (0·06)	0·32 3	15	0·24 (0·19)	0·16 (0·17)	0·29 367	34
5	0·22 (0·23)	0·15 (0·28)	0·26 57	34	0·18 (0·17)	0·19 (0·16)	0·26 36	47	0·24 (0·09)	0·07 (0·11)	0·25 8	16	0·20 —	0·28 —	0·35 1	55	No observations				0·21 (0·20)	0·16 (0·23)	0·26 102	37
6	0·13 (0·21)	0 (0·26)	0·13 24	0	0·11 (0·17)	0·09 (0·21)	0·14 16	39	0·25 (0·18)	0·04 (0·12)	0·26 5	9	0·07 —	0·23 —	0·24 1	73	No observations				0·13 (0·20)	0·04 (0·23)	0·14 46	17
All classes	0·26 (0·24)	0·15 (0·23)	0·30 444	30	0·27 (0·18)	0·14 (0·15)	0·31 392	27	0·31 (0·15)	0·12 (0·12)	0·34 231	21	0·36 (0·12)	0·11 (0·11)	0·38 88	17	0·44 (0·11)	0·08 (0·08)	0·44 29	10	0·29 (0·20)	0·17 (0·15)	0·33 1184	31

TABLE XIV. *Mean values of p, q, V_0/V_{900} and α for eight 900 mb wind direction classes and six lapse classes. (Standard deviations of p and q shown in parentheses; number of observations, comprising each group of four means, shown below mean V_0/V_{900})*

(a) OWS I (day-time and night-time)

900 mb wind direction class	N				NE				E				SE			
Lapse class	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°
1	0·98 (0·24)	0·05 (0·25)	0·98 83	−3	0·94 (0·19)	0·03 (0·15)	0·94 50	2	0·94 (0·17)	0·13 (0·27)	0·95 59	8	0·91 (0·30)	0·16 (0·27)	0·92 31	10
2	0·91 (0·24)	0·04 (0·25)	0·91 283	3	0·92 (0·22)	0·05 (0·25)	0·92 268	3	0·91 (0·24)	0·09 (0·27)	0·91 239	6	0·87 (0·21)	0·12 (0·21)	0·88 226	8
3	0·90 (0·23)	0·10 (0·36)	0·90 64	6	0·91 (0·23)	0·10 (0·25)	0·91 53	6	0·84 (0·30)	0·15 (0·25)	0·86 89	10	0·76 (0·21)	0·19 (0·22)	0·78 168	14
4	0·76 (0·28)	0·03 (0·59)	0·76 8	2	0·94 (0·33)	0·05 (0·28)	0·95 13	3	0·88 (0·27)	0·26 (0·24)	0·91 26	16	0·73 (0·24)	0·28 (0·27)	0·78 65	21
5	0·47 —	0·38 —	0·60 1	−39	0·86 —	(0) —	0·86 1	0	0·85 (0·29)	0·10 (0·23)	0·86 11	7	0·63 (0·20)	0·37 (0·26)	0·73 8	31
6	No observations				0·94 (0·18)	0·36 (0·48)	1·01 2	21	0·85 (0·15)	0·27 (0·25)	0·89 4	18	0·96 (0·20)	0·41 (0·21)	1·04 5	23
All classes	0·92 (0·25)	0·03 (0·28)	0·92 439	2	0·92 (0·22)	0·06 (0·25)	0·93 387	4	0·89 (0·25)	0·12 (0·27)	0·90 428	8	0·82 (0·23)	0·17 (0·24)	0·84 503	12

(b) OWS J (day-time and night-time)

900 mb wind direction class	N				NE				E				SE			
Lapse class	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°	p	q	V_0/V_{900}	α°
1	0·93 (0·27)	−0·05 (0·18)	0·93 33	−3	0·87 (0·49)	−0·11 (0·26)	0·88 19	−7	1·03 (0·34)	0·05 (0·32)	1·03 26	3	0·84 (0·21)	0·03 (0·31)	0·84 17	2
2	0·87 (0·27)	0·07 (0·26)	0·87 251	5	0·88 (0·30)	0·07 (0·29)	0·88 133	5	0·89 (0·24)	0·07 (0·26)	0·89 109	5	0·85 (0·25)	0·12 (0·27)	0·86 133	8
3	0·82 (0·42)	0·10 (0·36)	0·82 59	7	0·88 (0·33)	0·11 (0·34)	0·89 47	7	0·77 (0·24)	0·23 (0·28)	0·81 63	17	0·75 (0·26)	0·20 (0·19)	0·77 107	15
4	0·56 (0·77)	0·15 (0·37)	0·58 11	15	0·97 (0·36)	0·21 (0·26)	0·99 9	12	0·85 (0·17)	0·32 (0·27)	0·91 8	21	0·73 (0·23)	0·23 (0·20)	0·76 44	18
5	0·48 (0·44)	0·32 (0·17)	0·57 5	34	0·64 (0·28)	−0·02 (0·26)	0·64 3	−2	0·85 (0·13)	0·83 (1·04)	1·19 2	44	0·72 (0·16)	0·19 (0·22)	0·75 8	15
6	0·33 —	0·75 —	0·82 1	66	0·31 —	0·35 —	0·47 1	48	No observations				0·43 —	−0·35 —	0·56 1	−39
All classes	0·85 (0·34)	0·07 (0·28)	0·85 360	5	0·87 (0·33)	0·07 (0·30)	0·88 212	5	0·87 (0·26)	0·13 (0·31)	0·88 208	8	0·79 (0·25)	0·16 (0·24)	0·81 310	11

TABLE XIV (*continued*)

(*a*) *OWS I* (*day-time and night-time*)

900 mb wind direction class	S				SW				W				NW			
Lapse class	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$
1	0·85	0·07	0·86	5	0·84	0·03	0·84	2	0·85	−0·01	0·85	−1	0·90	0·05	0·90	−3
	(0·21)	(0·34)	37		(0·16)	(0·20)	118		(0·16)	(0·18)	169		(0·17)	(0·22)	105	
2	0·79	0·14	0·80	10	0·77	0·07	0·78	5	0·84	0·02	0·84	1	0·88	0·03	0·88	2
	(0·19)	(0·25)	340		(0·22)	(0·23)	543		(0·17)	(0·21)	711		(0·23)	(0·24)	372	
3	0·71	0·23	0·74	18	0·68	0·15	0·70	12	0·75	0·08	0·75	6	0·89	0·11	0·90	7
	(0·22)	(0·25)	295		(0·20)	(0·26)	335		(0·25)	(0·31)	193		(0·27)	(0·32)	100	
4	0·67	0·25	0·72	20	0·64	0·22	0·68	19	0·69	0·16	0·71	13	0·78	0·19	0·80	14
	(0·19)	(0·27)	101		(0·23)	(0·28)	132		(0·17)	(0·20)	78		(0·33)	(0·33)	26	
5	0·64	0·22	0·68	19	0·60	0·19	0·63	18	0·70	0·13	0·72	11	0·70	0·27	0·75	21
	(0·24)	(0·15)	37		(0·25)	(0·22)	44		(0·26)	(0·20)	31		(0·12)	(0·22)	8	
6	0·79	0·51	0·94	33	0·65	0·21	0·69	18	0·68	0·26	0·73	21	0·68	0·36	0·77	28
	(0·18)	(0·35)	6		(0·10)	(0·15)	5		(0·23)	(0·20)	10		(0·06)	(0·01)	3	
All classes	0·74	0·19	0·76	14	0·73	0·11	0·74	9	0·81	0·04	0·81	3	0·88	0·04	0·88	3
	(0·21)	(0·26)	816		(0·22)	(0·25)	1177		(0·20)	(0·23)	1192		(0·23)	(0·26)	614	

(*b*) *OWS J* (*day-time and night-time*)

900 mb wind direction class	S				SW				W				NW			
Lapse class	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$
1	0·83	0·05	0·83	3	0·78	0·06	0·78	4	0·85	0·01	0·85	1	0·89	0·02	0·89	1
	(0·15)	(0·28)	18		(0·17)	(0·19)	47		(0·17)	(0·17)	122		(0·15)	(0·23)	80	
2	0·80	0·16	0·81	11	0·73	0·11	0·73	9	0·77	0·03	0·78	2	0·86	0·04	0·86	3
	(0·19)	(0·21)	199		(0·21)	(0·28)	351		(0·21)	(0·21)	656		(0·23)	(0·22)	459	
3	0·70	0·25	0·75	20	0·67	0·16	0·69	13	0·70	0·11	0·71	9	0·82	0·03	0·82	2
	(0·29)	(0·26)	235		(0·21)	(0·22)	303		(0·20)	(0·25)	299		(0·29)	(0·35)	128	
4	0·63	0·28	0·69	24	0·61	0·25	0·66	22	0·57	0·21	0·60	20	0·77	0·13	0·78	10
	(0·27)	(0·25)	110		(0·20)	(0·22)	244		(0·23)	(0·31)	166		(0·26)	(0·35)	40	
5	0·53	0·28	0·60	28	0·63	0·25	0·68	22	0·57	0·18	0·60	18	0·73	0·04	0·73	3
	(0·18)	(0·14)	22		(0·20)	(0·21)	68		(0·25)	(0·28)	62		(0·09)	(0·25)	9	
6	0·67	0·19	0·70	16	0·48	0·20	0·52	23	0·55	0·31	0·64	29	0·69	0·22	0·73	18
	(0·07)	(0·09)	2		(0·21)	(0·05)	3		(0·16)	(0·18)	11		(0·13)	(0·16)	4	
All classes	0·72	0·22	0·75	17	0·67	0·17	0·69	14	0·73	0·08	0·73	6	0·85	0·04	0·85	3
	(0·26)	(0·25)	586		(0·21)	(0·25)	1016		(0·22)	(0·24)	1316		(0·23)	(0·25)	720	

TABLE XIV (*continued*)

(*c*) *Heathrow* (*day-time and night-time*)

900 mb wind direction class	N				NE				E				SE				S			
Lapse class	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$
1	0·55	0·06	0·55	6	0·61	−0·01	0·61	−1	0·64	0·04	0·65	3	0·67	−0·06	0·68	−5	0·57	−0·04	0·57	−4
	(0·16)	(0·19)	9		(0·26)	(0·16)	25		(0·21)	(0·24)	12		(0·26)	(0·26)	5		(0·31)	(0·28)	10	
2	0·54	0·02	0·54	2	0·52	0·03	0·52	4	0·65	0·04	0·65	3	0·60	0·15	0·61	14	0·57	0·07	0·58	7
	(0·22)	(0·27)	83		(0·18)	(0·19)	116		(0·19)	(0·25)	50		(0·23)	(0·32)	48		(0·24)	(0·16)	46	
3	0·32	0·14	0·35	24	0·39	0·15	0·42	21	0·49	0·11	0·51	13	0·35	0·25	0·43	36	0·38	0·21	0·43	29
	(0·22)	(0·15)	131		(0·20)	(0·15)	137		(0·25)	(0·21)	72		(0·38)	(0·22)	46		(0·20)	(0·16)	109	
4	0·24	0·12	0·27	26	0·30	0·18	0·36	32	0·35	0·21	0·41	31	0·30	0·31	0·43	47	0·21	0·23	0·32	48
	(0·17)	(0·17)	95		(0·21)	(0·14)	85		(0·21)	(0·20)	69		(0·18)	(0·21)	46		(0·18)	(0·21)	119	
5	0·10	0·14	0·17	54	0·31	0·08	0·32	14	0·33	0·25	0·41	38	0·24	0·30	0·38	51	0·11	0·26	0·28	68
	(0·15)	(0·17)	18		(0·21)	(0·16)	44		(0·19)	(0·22)	42		(0·20)	(0·24)	39		(0·19)	(0·18)	55	
6	0·17	0·11	0·21	33	0·32	0·05	0·32	10	0·28	0·24	0·37	41	0·18	0·29	0·35	58	0·13	0·21	0·25	59
	(0·16)	(0·13)	7		(0·19)	(0·16)	18		(0·22)	(0·12)	33		(0·14)	(0·21)	27		(0·20)	(0·17)	30	
All classes	0·34	0·10	0·36	16	0·41	0·11	0·43	15	0·44	0·16	0·47	20	0·36	0·25	0·44	35	0·29	0·20	0·36	35
	(0·24)	(0·20)	343		(0·22)	(0·18)	425		(0·25)	(0·23)	278		(0·29)	(0·26)	211		(0·25)	(0·18)	369	

(*d*) *Leuchars* (*day-time and night-time*)

900 mb wind direction class	N				NE				E				SE				S			
Lapse class	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$
1	0·37	0·16	0·40	−24	0·58	0·21	0·62	−19	0·66	0·17	0·68	14	0·80	0·20	0·82	14	0·54	0·14	0·56	15
	(0·28)	(0·37)	34		(0·33)	(0·33)	12		(0·10)	(0·11)	8		(0·44)	(0·19)	8		(0·18)	(0·43)	19	
2	0·31	0·04	0·32	7	0·47	0·02	0·47	2	0·58	0·09	0·59	8	0·54	0·12	0·55	12	0·31	0·23	0·39	37
	(0·23)	(0·18)	62		(0·28)	(0·27)	44		(0·19)	(0·21)	59		(0·21)	(0·23)	60		(0·22)	(0·27)	46	
3	0·20	0·17	0·26	39	0·34	0·10	0·35	16	0·51	0·13	0·53	14	0·44	0·23	0·49	27	0·27	0·17	0·32	32
	(0·17)	(0·23)	71		(0·25)	(0·21)	60		(0·15)	(0·21)	67		(0·22)	(0·22)	77		(0·20)	(0·19)	78	
4	0·05	0·23	0·24	79	0·02	0·17	0·18	86	0·36	0·27	0·45	37	0·35	0·25	0·43	35	0·29	0·20	0·35	35
	(0·12)	(0·24)	25		(0·34)	(0·19)	18		(0·24)	(0·14)	31		(0·26)	(0·21)	65		(0·19)	(0·19)	57	
5	0·01	0·12	0·12	88	(0)	0·04	0·04	89	0·26	0·34	0·43	52	0·13	0·31	0·33	68	0·20	0·14	0·24	34
	(0·10)	(0·17)	6		(0·32)	(0·19)	6		(0·13)	(0·08)	5		(0·21)	(0·20)	23		(0·18)	(0·19)	23	
6	0·05	0·61	0·62	95	−0·04	0·01	0·04	172	−0·02	0·07	0·07	103	(0)	0·28	0·28	90	0·06	−0·03	0·07	−29
	—	—	1		—	—	1		(0·21)	(0·09)	2		(0·13)	(0·17)	12		(0·19)	(0·29)	11	
All classes	0·24	0·08	0·25	18	0·34	0·05	0·35	8	0·50	0·15	0·52	17	0·40	0·21	0·46	28	0·29	0·17	0·34	30
	(0·22)	(0·28)	199		(0·33)	(0·26)	141		(0·21)	(0·21)	172		(0·28)	(0·22)	245		(0·22)	(0·24)	234	

TABLE XIV (*continued*)

(*c*) *Heathrow* (*day-time and night-time*)

900 mb wind direction class	SW				W				NW				All directions			
Lapse class	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$
1	0·72	0·05	0·73	4	0·62	−0·02	0·62	−2	0·67	0·04	0·67	3	0·64	0·01	0·64	1
	(0·21)	(0·22)	17		(0·27)	(0·20)	22		(0·29)	(0·22)	19		(0·26)	(0·22)	119	
2	0·62	0·08	0·62	7	0·61	0·03	0·61	3	0·55	0·12	0·57	12	0·59	0·06	0·59	6
	(0·23)	(0·22)	198		(0·23)	(0·20)	212		(0·21)	(0·18)	126		(0·22)	(0·22)	879	
3	0·39	0·15	0·42	23	0·41	0·15	0·44	19	0·35	0·12	0·37	19	0·39	0·15	0·42	21
	(0·18)	(0·14)	347		(0·16)	(0·16)	272		(0·18)	(0·20)	172		(0·20)	(0·17)	1286	
4	0·29	0·17	0·33	30	0·30	0·16	0·34	29	0·25	0·18	0·31	35	0·28	0·18	0·33	32
	(0·18)	(0·16)	302		(0·15)	(0·14)	329		(0·14)	(0·13)	186		(0·17)	(0·15)	1231	
5	0·22	0·19	0·29	40	0·23	0·15	0·27	32	0·22	0·21	0·30	44	0·22	0·19	0·30	41
	(0·20)	(0·17)	72		(0·16)	(0·16)	83		(0·12)	(0·13)	33		(0·20)	(0·19)	386	
6	0·20	0·17	0·27	40	0·27	0·16	0·32	31	0·21	0·20	0·29	45	0·22	0·19	0·30	41
	(0·27)	(0·18)	36		(0·23)	(0·16)	32		(0·14)	(0·15)	6		(0·22)	(0·18)	189	
All classes	0·39	0·14	0·42	20	0·40	0·12	0·42	17	0·37	0·14	0·39	21	0·38	0·14	0·41	20
	(0·24)	(0·17)	972		(0·22)	(0·17)	950		(0·22)	(0·18)	542		(0·24)	(0·19)	4090	

(*d*) *Leuchars* (*day-time and night-time*)

900 mb wind direction class	SW				W				NW				All directions			
Lapse class	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$	p	q	V_0/V_{900}	$\alpha°$
1	0·57	0·01	0·57	1	0·60	0·08	0·61	8	0·52	0·06	0·52	7	0·56	0·04	0·56	4
	(0·21)	(0·21)	76		(0·19)	(0·21)	139		(0·30)	(0·26)	68		(0·25)	(0·27)	364	
2	0·42	0·05	0·42	6	0·45	0·14	0·47	17	0·39	0·15	0·42	21	0·44	0·10	0·45	13
	(0·21)	(0·18)	122		(0·25)	(0·17)	128		(0·24)	(0·24	77		(0·24)	(0·22)	598	
3	0·30	0·05	0·30	9	0·35	0·15	0·38	23	0·22	0·22	0·31	45	0·32	0·15	0·35	24
	(0·20)	(0·16)	170		(0·18)	(0·13)	225		(0·19)	(0·17)	126		(0·21)	(0·19)	874	
	0·25	0·04	0·27	8	0·28	0·13	0·31	25	0·19	0·31	0·36	59	0·25	0·17	0·31	33
	(0·18)	(0·13)	115		(0·20)	(0·12)	131		(0·13)	(0·18)	59		(0·22)	(0·19)	501	
5	0·23	0·03	0·23	7	0·35	0·09	0·36	15	0·19	0·42	0·46	65	0·21	0·16	0·27	38
	(0·21)	(0·20)	30		(0·13)	(0·12)	29		(0·15)	(0·21)	13		(0·21)	(0·22)	135	
6	0·21	−0·05	0·21	−13	0·22	0·02	0·22	4	0·21	0·29	0·36	53	0·13	0·05	0·14	23
	(0·18)	(0·15)	20		(0·17)	(0·08)	12		—	—	1		(0·19)	(0·23)	60	
All classes	0·35	0·03	0·35	5	0·41	0·13	0·42	18	0·31	0·20	0·37	33	0·36	0·12	0·38	19
	(0·23)	(0·17)	533		(0·23)	(0·16)	664		(0·25)	(0·23)	344		(0·25)	(0·22)	2532	

NOTES ON THE FIGURES

1. *Lapse classes*

Lapse classes are identified either by the lapse-class number shown beside the plotted point or by plotting the points in the following code:

Lapse class	1	2	3	4	5	6
Code	•	×	⊗	□	○	△

2. 900 *mb wind speed classes*

The 900 mb wind speed classes are labelled as follows for brevity:

900 mb wind speed class (kt)	10–19,	20–29,	30–39,	40–49,	⩾ 50
Label in figures	15	25	35	45	> 50

Where the 900 mb wind speed class is represented along one of the axes in the figures, the classes are spaced at equal intervals for convenience. The spacing implies a linear scale from 'class 15' to 'class 45' inclusive, but not below 10 kt or above 49 kt because all 900 mb wind speeds below 10 kt were excluded from the analysis and all 900 mb wind speeds above 49 kt were grouped into a single class the mean of which is 57 kt for the ocean weather stations and 55 kt for the land stations. The means for the highest wind speed class are connected to the means for 'class 45' by pecked lines only.

3. 900 *mb wind direction classes*

The 900 mb wind direction classes are labelled with the direction letters corresponding to the mid-point of each 45° sector.

4. *Observations used to compute the means*

Where there is space in the figures, the number of observations used to compute each mean is shown in brackets beside each plotted point. Where there is insufficient space a value is inserted only if the number of observations is less than 15.

5. Minor discrepancies occur between the Heathrow analyses of day-time and night-time observations treated separately and all observations combined. The discrepancy is eight in a grand total of 4090 observations and cannot have any material effect on the means quoted.

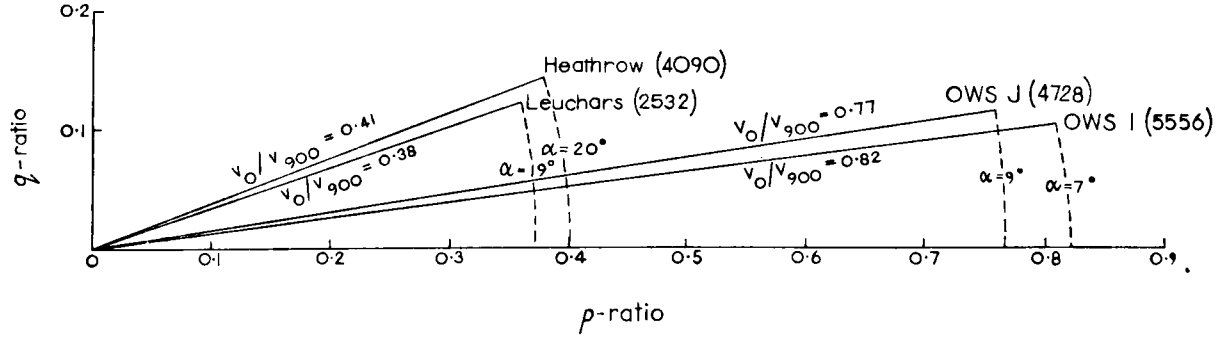


FIGURE 1. Overall mean p- and q-ratios, V_0/V_{900}, and α.

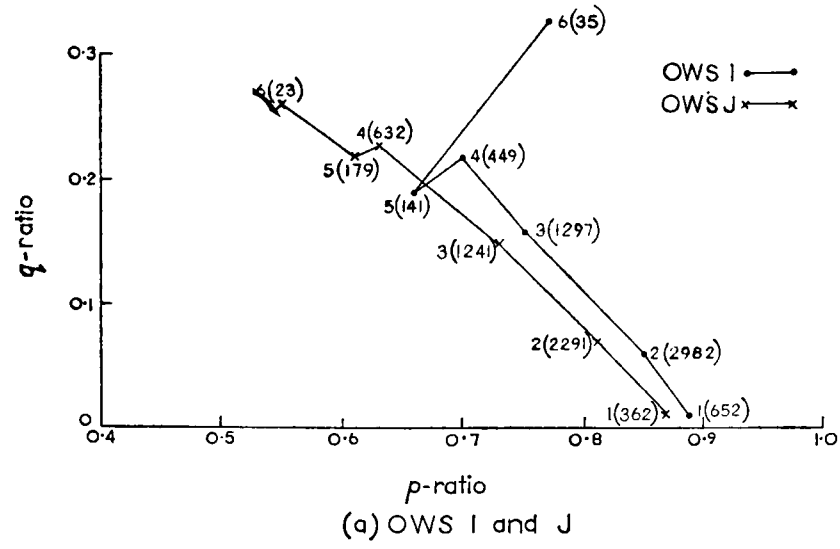


FIGURE 2. Mean p- and q-ratios in six lapse classes (see notes 1 and 4).

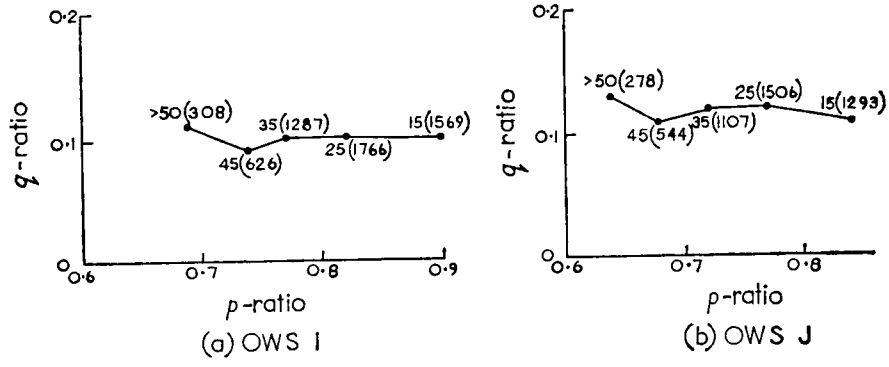


FIGURE 3. Mean p- and q-ratios in five 900 mb wind speed classes (see notes 2 and 4).

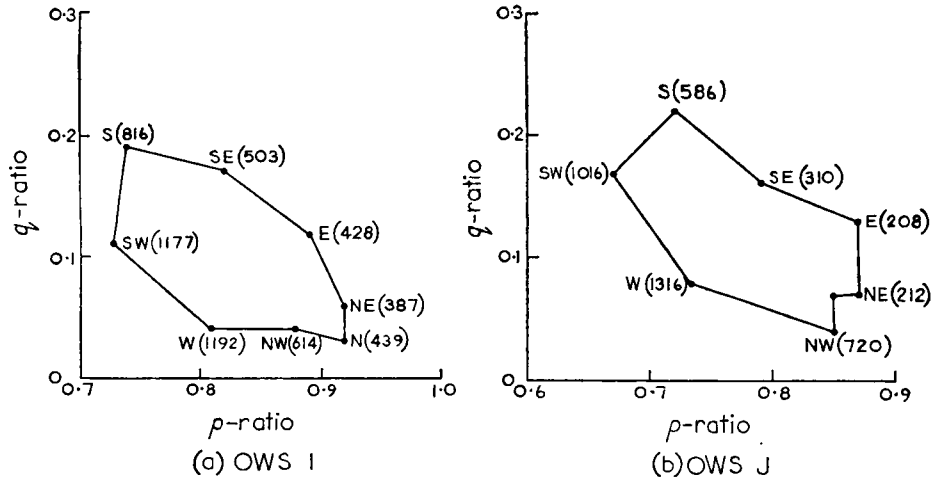
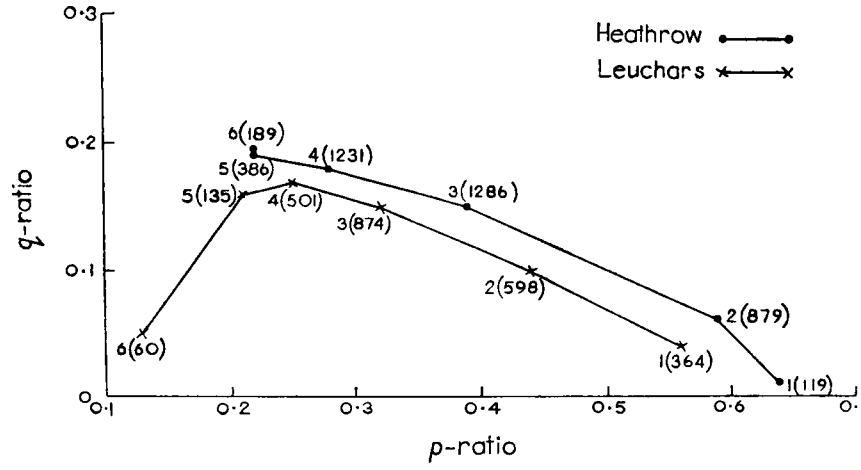
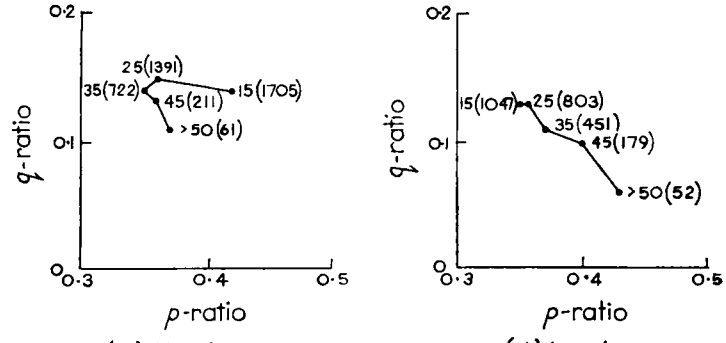


FIGURE 4. Mean p- and q-ratios in eight 900 mb wind direction classes (see notes 3 and 4).



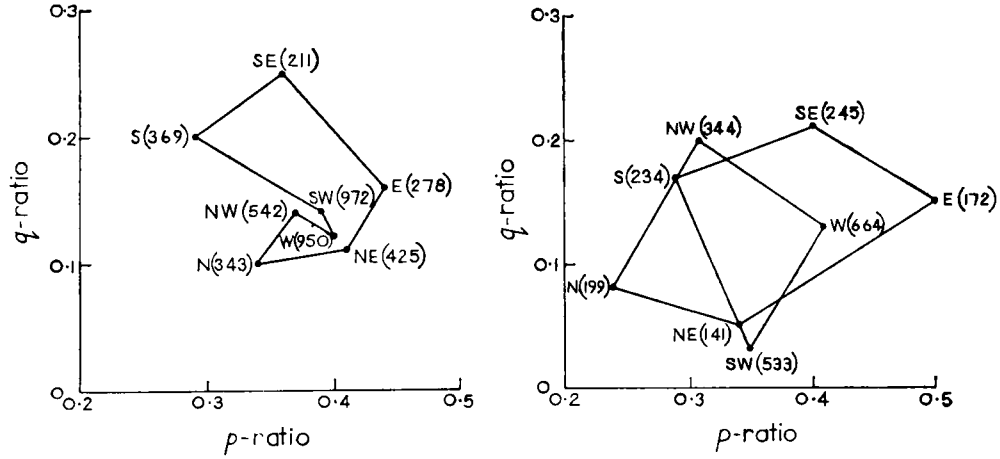
(b) Heathrow and Leuchars

FIGURE 2 (*continued*).



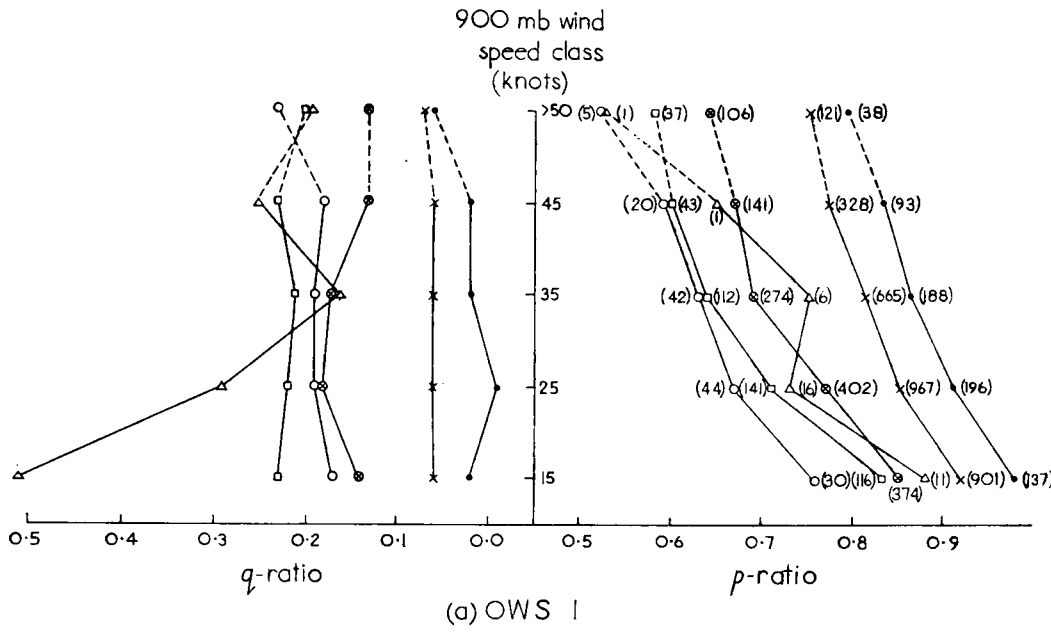
(c) Heathrow (d) Leuchars

FIGURE 3 (*continued*).



(c) Heathrow (d) Leuchars

FIGURE 4 (*continued*).



Some p- and q-ratios for exceptionally strong winds

OWS I					OWS I					OWS J				
900 mb wind				Lapse	900 mb wind				Lapse	900 mb wind				Lapse
degrees	kt	p	q	class	degrees	kt	p	q	class	degrees	kt	p	q	class
232	72	0·81	0·04	1	226	97	0·70	–0·04	2	022	60	1·00	0	1
223	75	0·85	0·14	1	241	58	1·00	0	3	352	66	0·91	0·05	2
325	52	1·06	0	2	253	76	0·79	–0·08	3	169	60	0·76	0·38	3
178	75	0·80	–0·04	2										

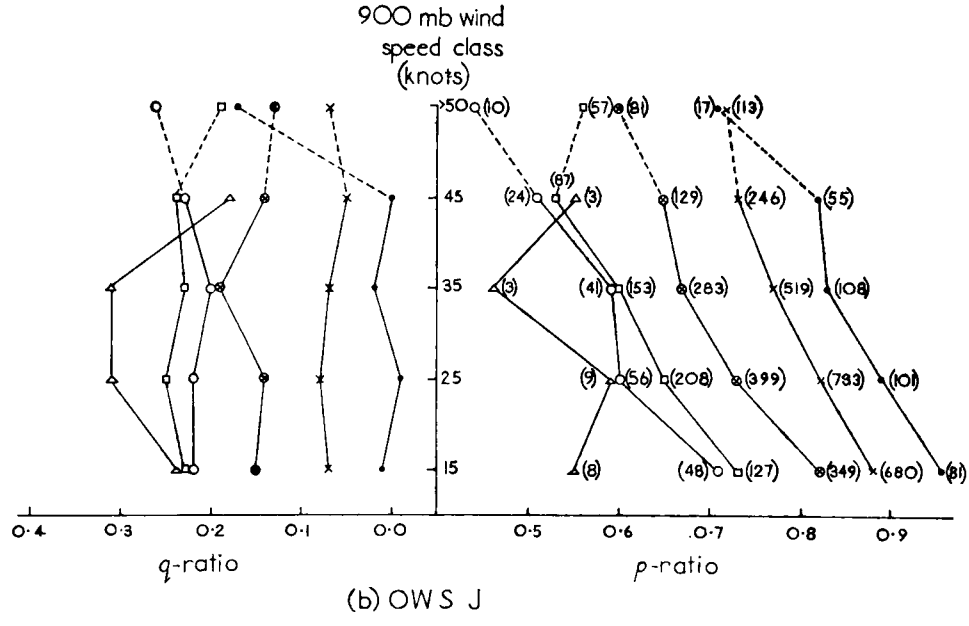
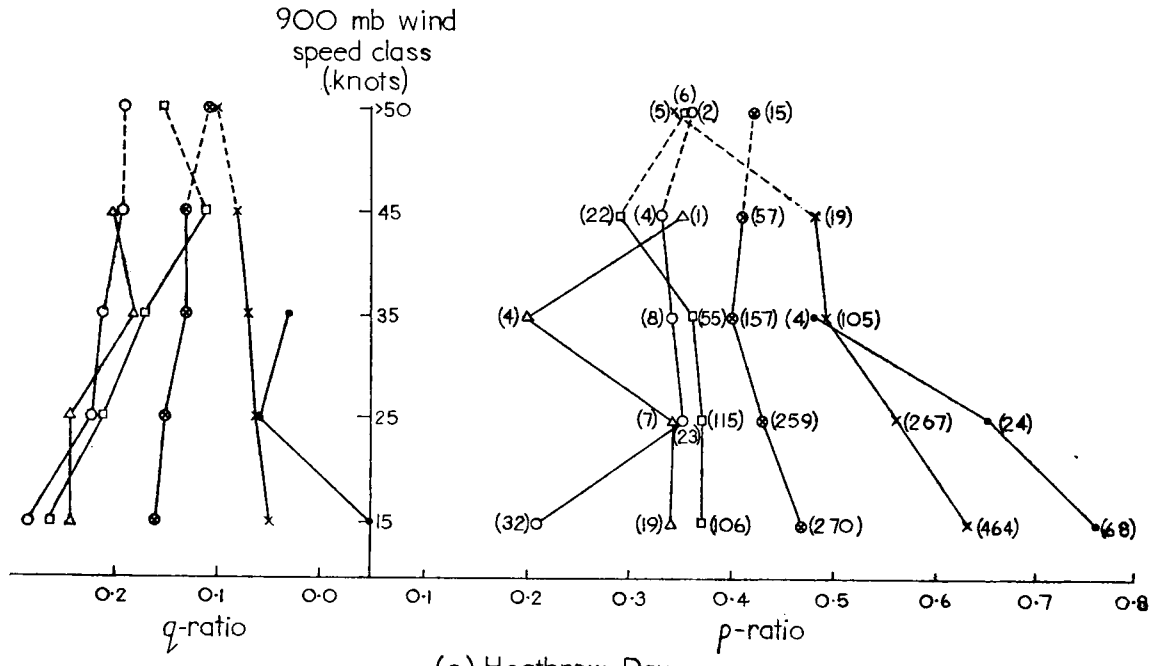
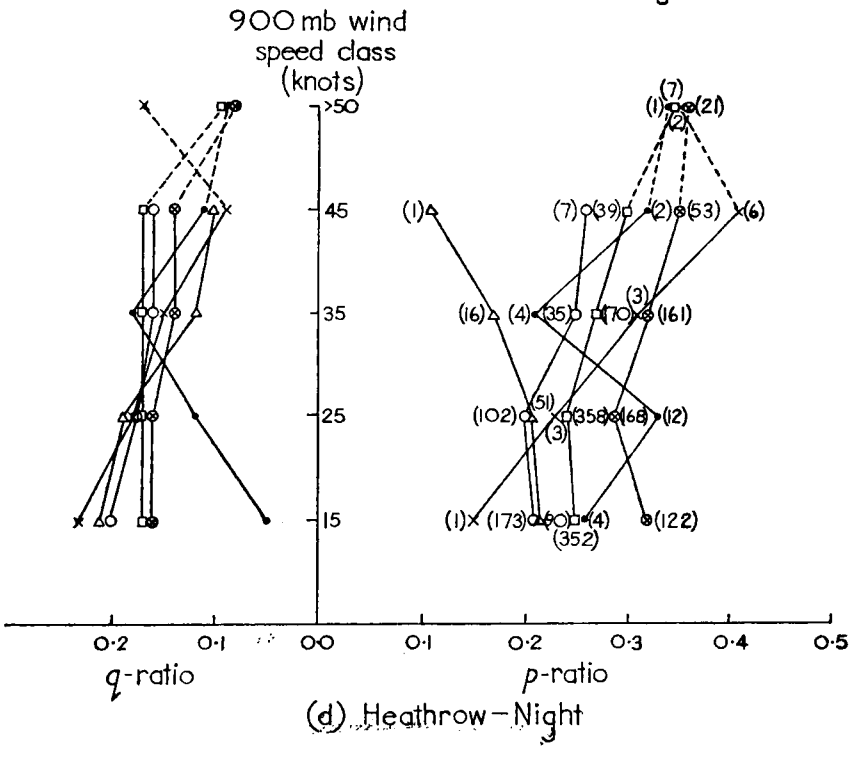


FIGURE 5. Mean p- and q-ratios in six lapse classes and five 900 mb wind speed classes (see notes 1 and 4).



(c) Heathrow-Day



(d) Heathrow–Night

FIGURE 5 (*continued*).

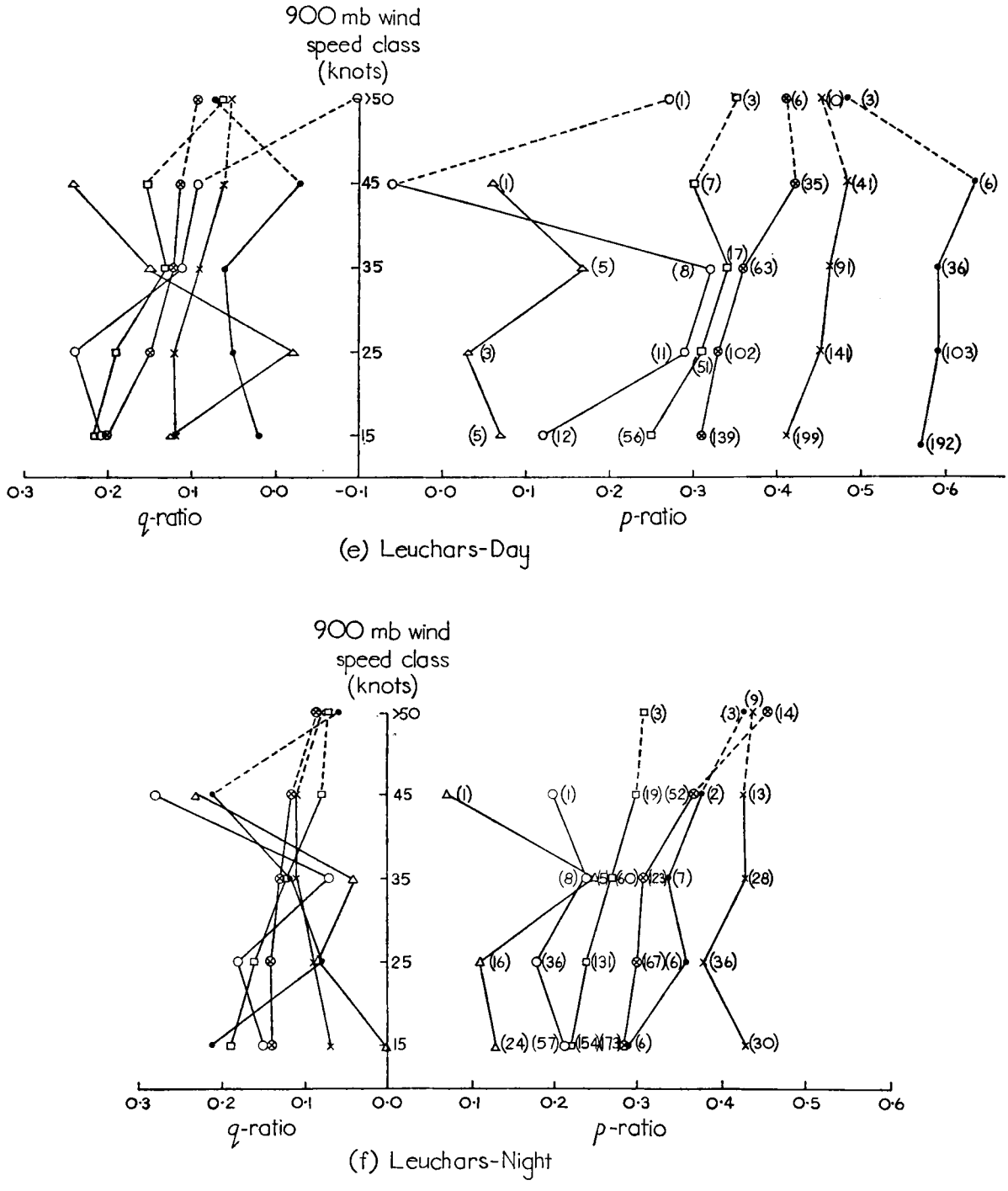


FIGURE 5. Mean p- and q-ratios in six lapse classes and five 900 mb wind speed classes (see notes 1 and 4).

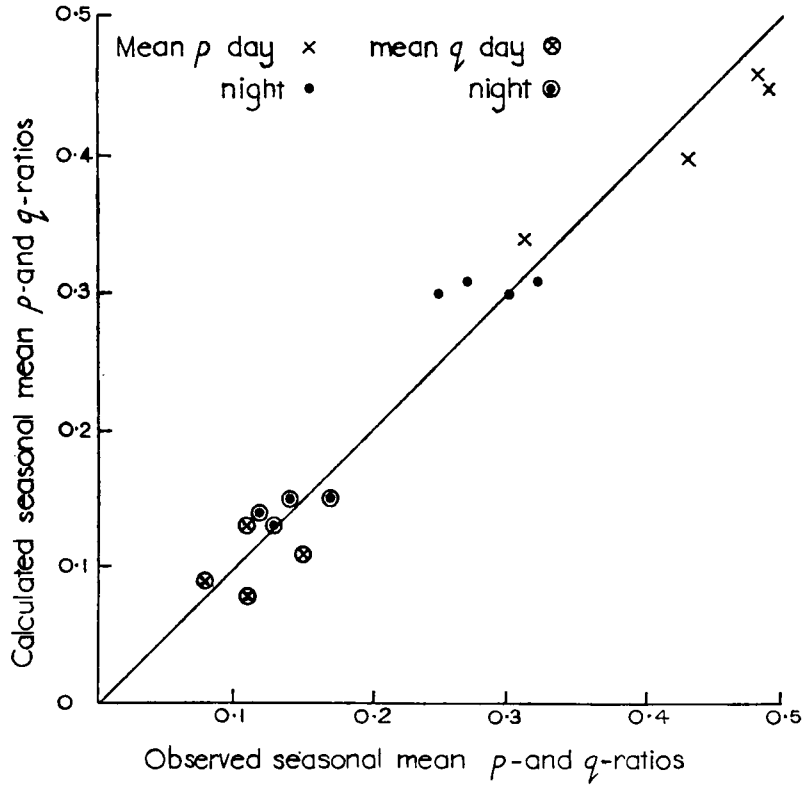


FIGURE 6. Comparison of seasonal p- and q-ratios, day and night observations separately, with means derived from lapse-class frequencies—Leuchars.

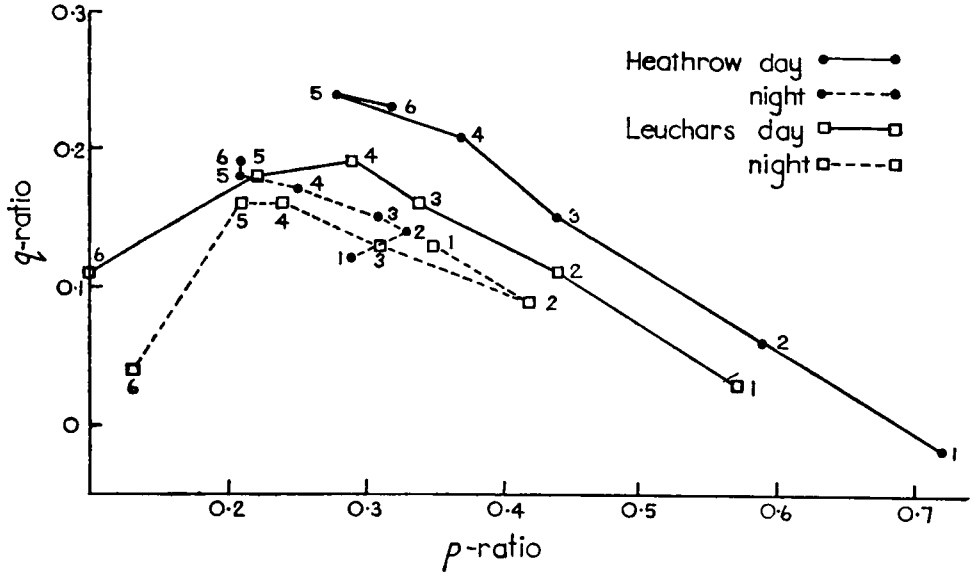
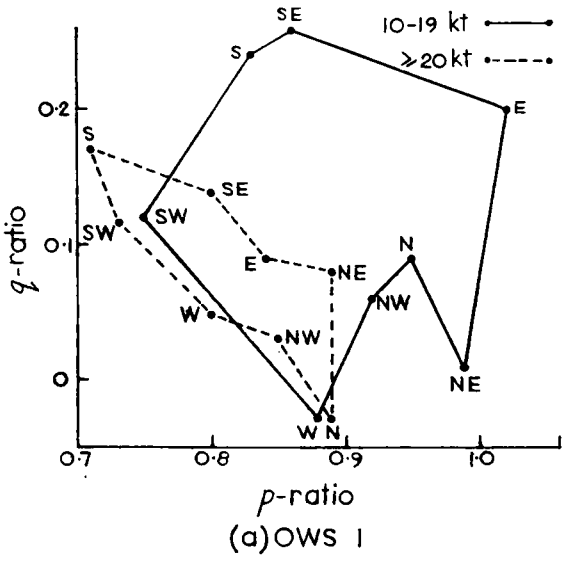
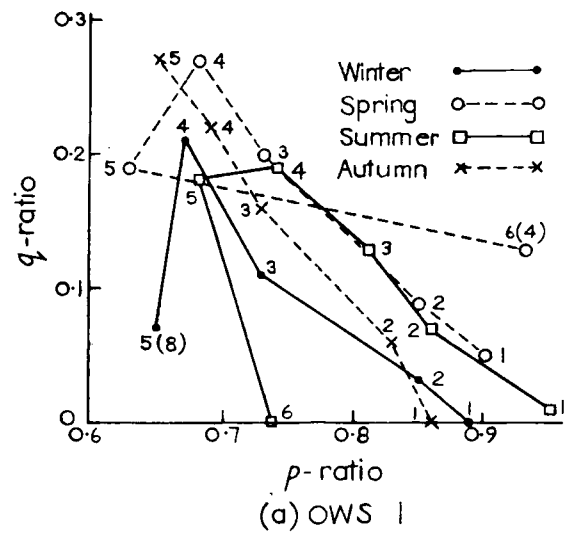
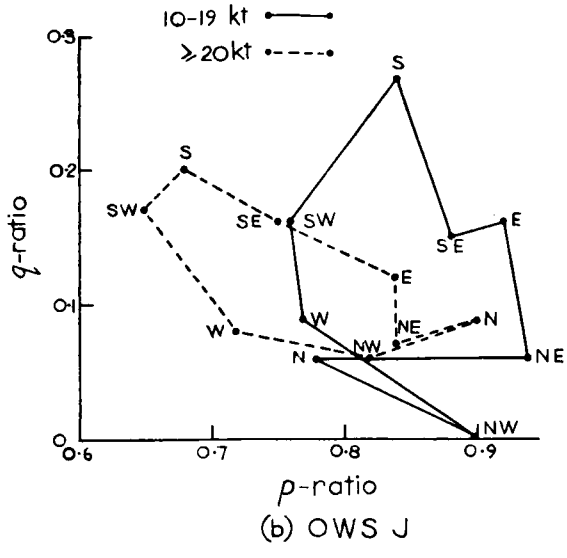


FIGURE 7. Day-time and night-time mean p- and q-ratios in six lapse classes—Heathrow and Leuchars.







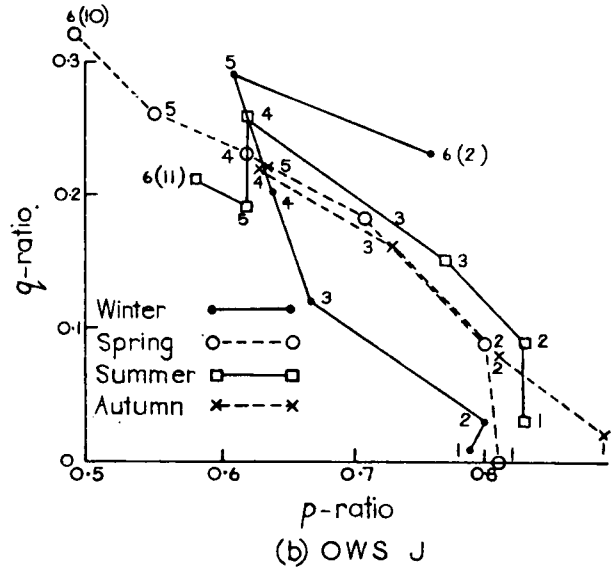


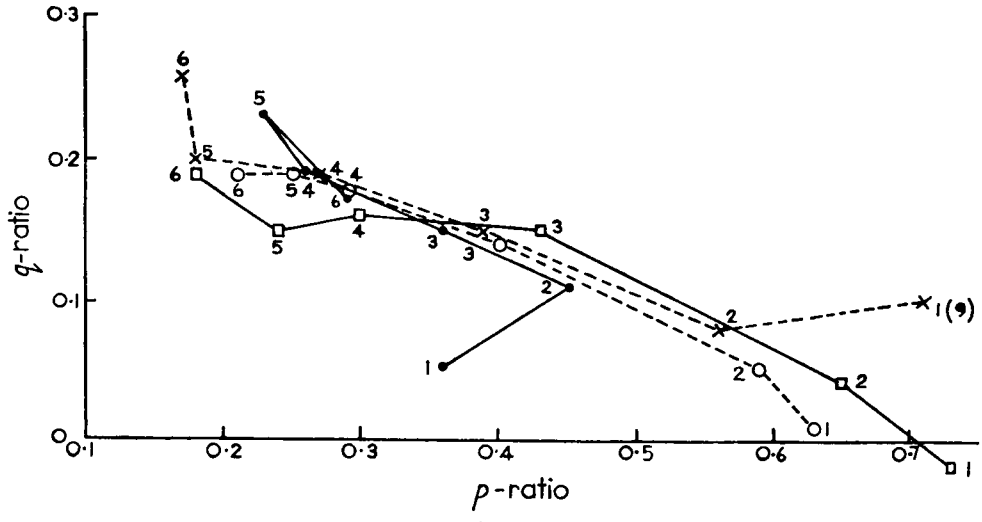
FIGURE 8. Mean p- and q-ratios in eight 900 mb wind direction classes for 900 mb wind speeds 10–19 kt and $\geqslant$ 20 kt separately.

FIGURE 9. Mean p- and q-ratios for four seasons (see notes 1 and 4).

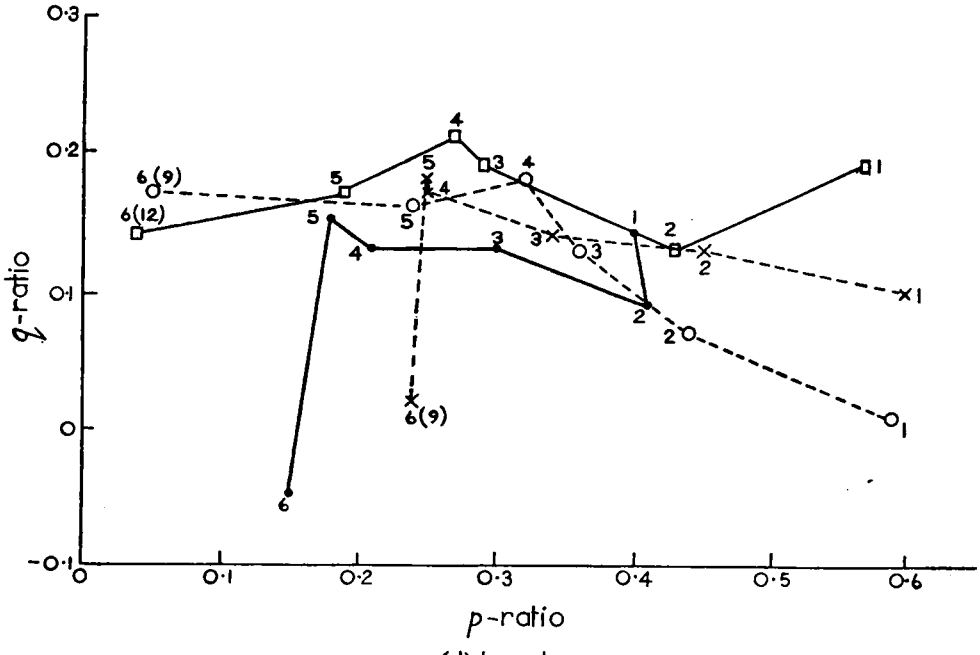
NOTE. In Figure 9 (*a*) it was necessary for reasons of space to omit two points as follows:

(i) Lapse class 6, winter, $p=0{\cdot}89$, $q=-0{\cdot}19$, 1 observation.

(ii) Lapse class 6, autumn, $p=0{\cdot}80$, $q=0{\cdot}56$, 4 observations.



(c) Heathrow



(d) Leuchars

FIGURE 9 (*continued*).

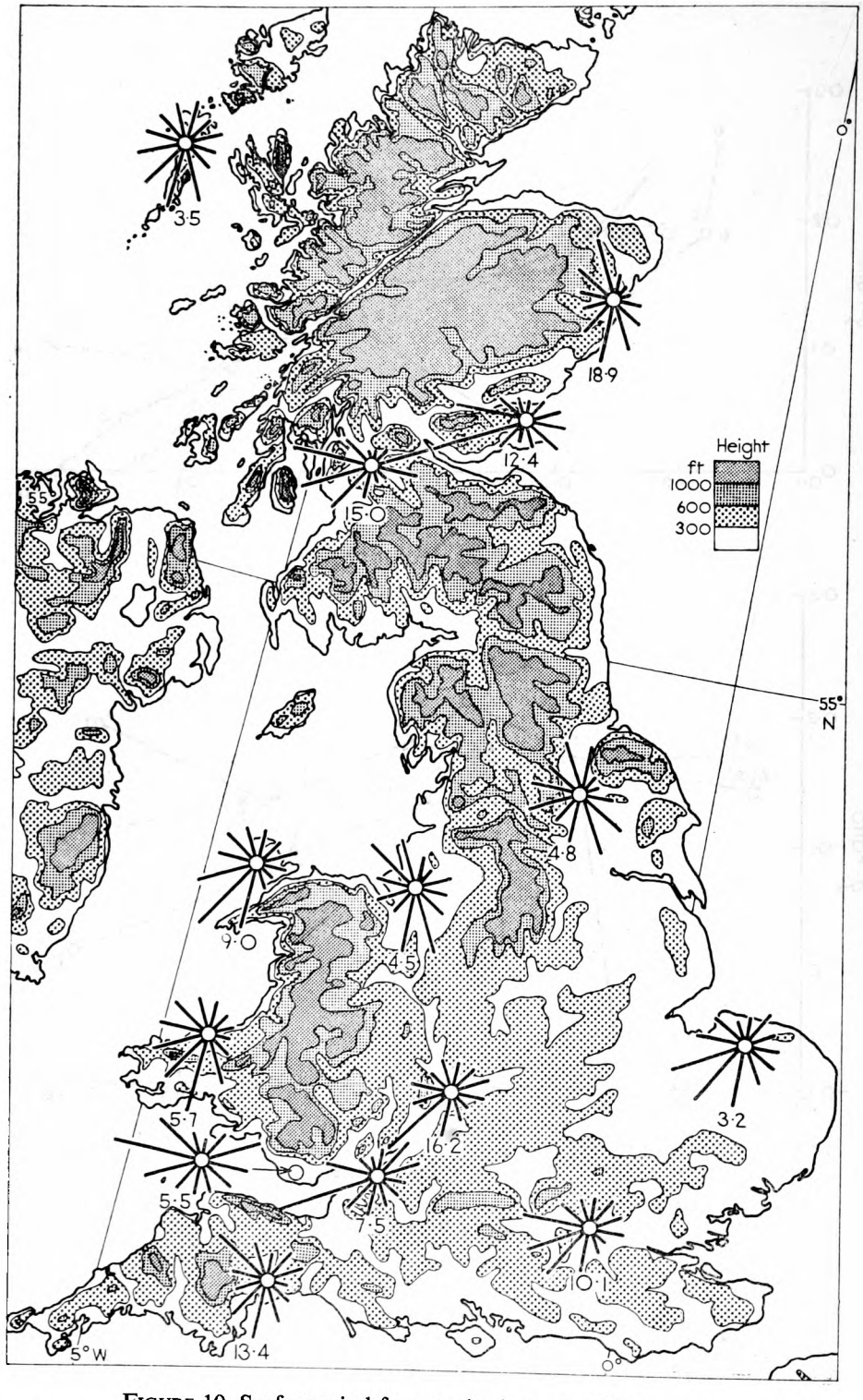


FIGURE 10. Surface wind frequencies in twelve 30°-sectors.
Scale: 6 mm represents 10 per cent of the observations for each wind rose.
Percentage of calms shown below each station circle.

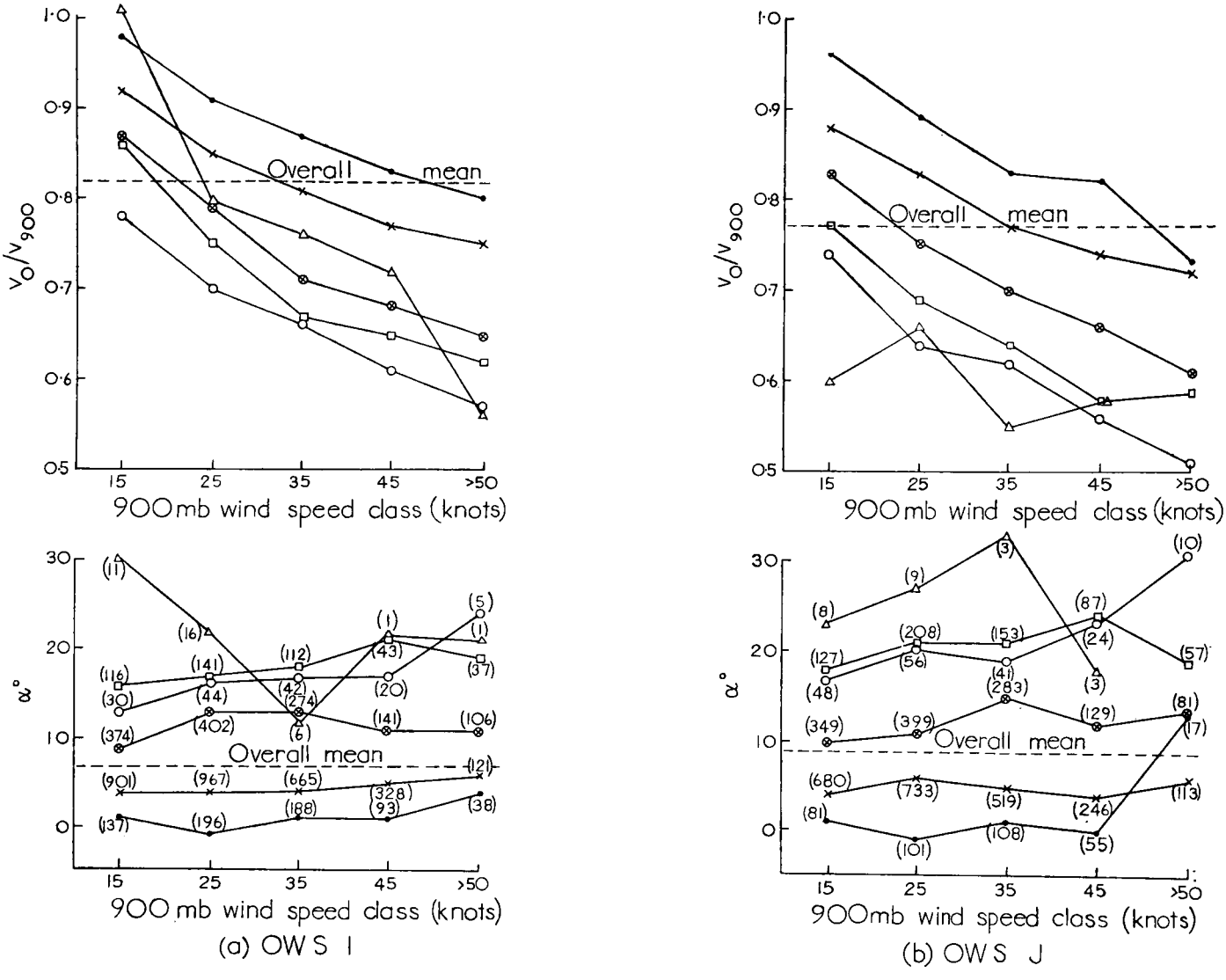


FIGURE 11. Mean V_0/V_{900} and α in six lapse classes and five 900 mb wind speed classes.

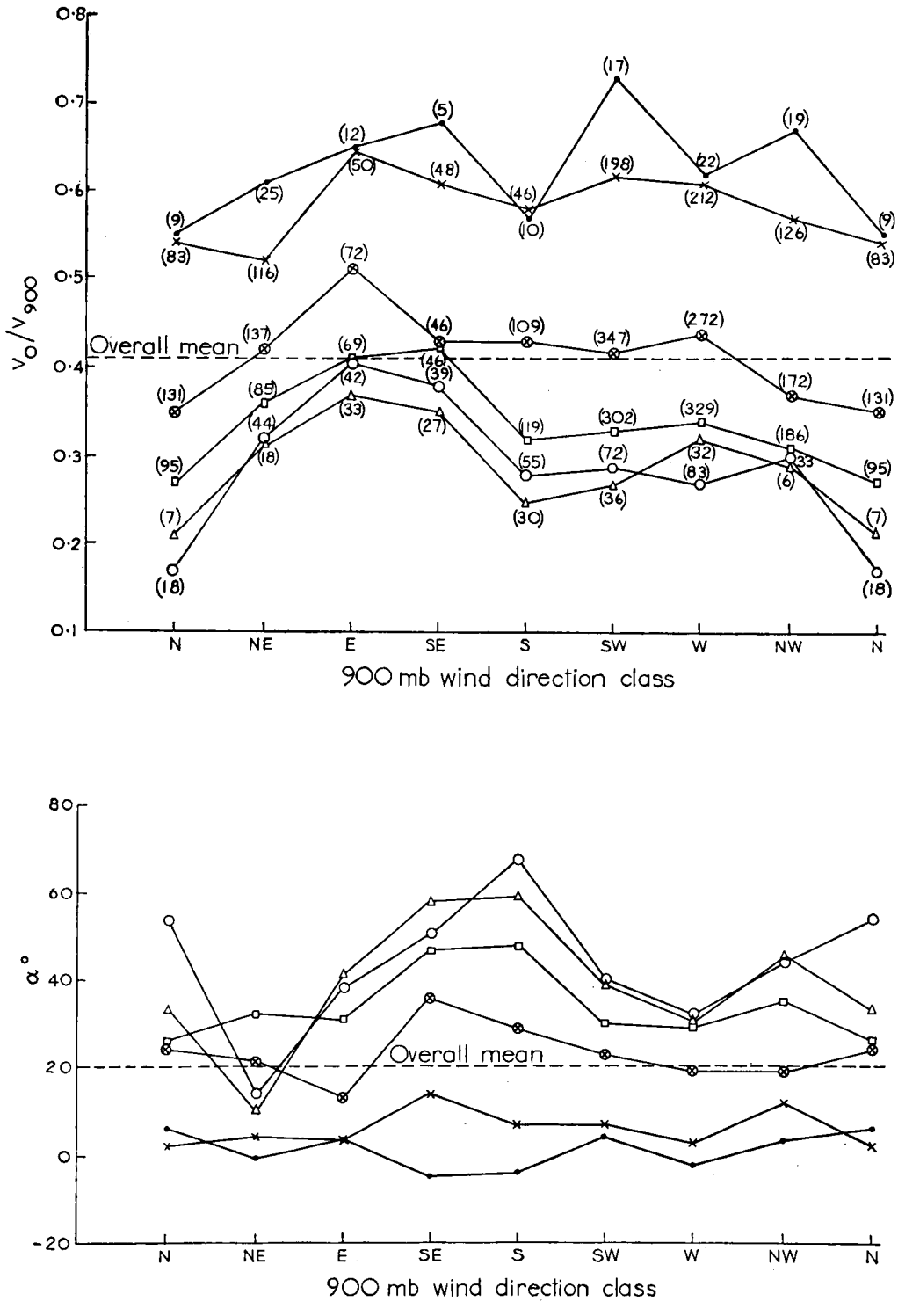


FIGURE 12. Mean V_0/V_{900} and α in six lapse classes and eight 900 mb wind direction classes—Heathrow.

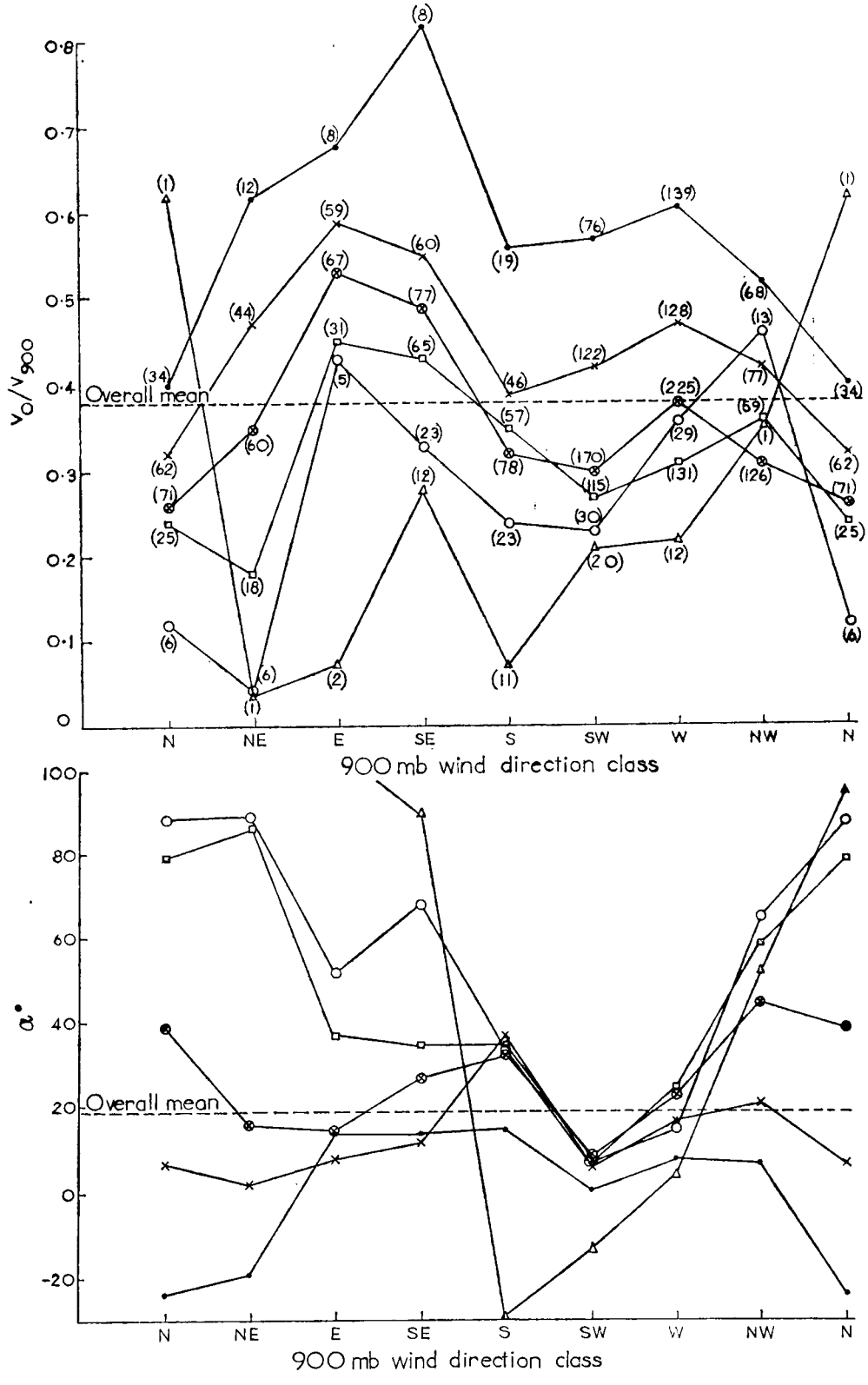


FIGURE 13. Mean V_0/V_{900} and α in six lapse classes and eight 900 mb wind direction classes—Leuchars.

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